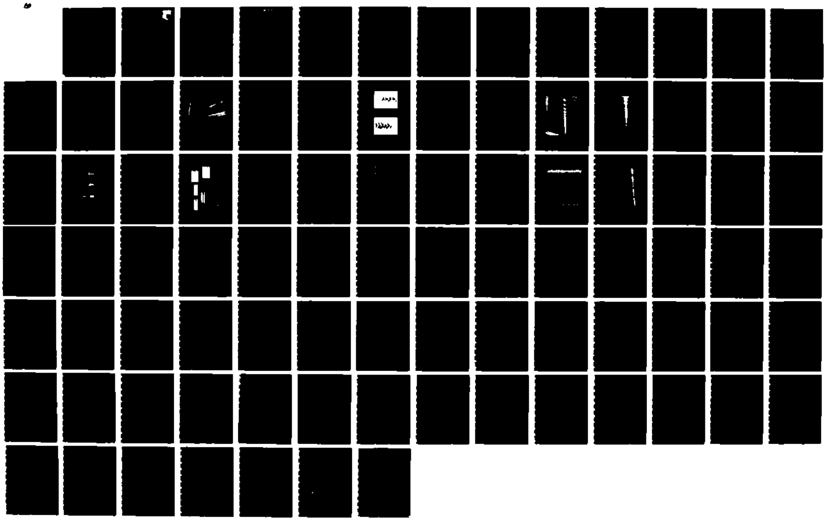
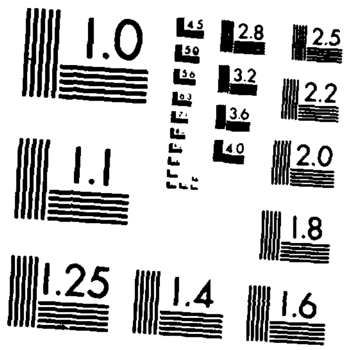
AD-A174 323 STRAIN GAGE SIGNAL INTERPRETATION(U) GENERAL ELECTRIC CO CINCINNATI OH AIRCRAFT ENGINE BUSINESS GROUP R B FOST ET AL FEB 86 R85AEB440 AFWAL-TR-85-2098 1/1

UNCLASSIFIED F33615-83-C-2334 F/G 14/2 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

(2)

AFWAL-TR-85-2098

Strain Gage Signal Interpretation

R.B. Fost
V.C. Gallardo
W.R. Stowell

General Electric Cc..ıpany
Aircraft Engine Business Group
Advanced Technology Programs Department
Cincinnati, OH 45215

February 1986

Final Report for Period June 1983 - July 1985

Approved for public release; distribution is unlimited

Aero Propulsion Laboratory
Air Force Wright Aeronautical Laboratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433-6563

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

ROBERT D. DEROSE
Project Engineer

WALKER H. MITCHELL
Chief, Technology Branch

FOR THE COMMANDER

MICHAEL E. STEFKOVICH, Major, USAF
Deputy Director
Turbine Engine Division

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFWAL/POTX, W-PAFB, OH 45433 to help us maintain a current mailing list."

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

AD-A174 333

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS None
2a. SECURITY CLASSIFICATION AUTHORITY NA	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE NA	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) R85AEB440	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFWAL-TR-85-2098
6a. NAME OF PERFORMING ORGANIZATION General Electric Company 6b. OFFICE SYMBOL (If applicable) NA	7a. NAME OF MONITORING ORGANIZATION Air Force Wright Aeronautical Laboratories Aero Propulsion Laboratory (AFWAL/POTX)
6c. ADDRESS (City, State and ZIP Code) Aircraft Engine Business Group Advanced Technology Programs Department Cincinnati, Ohio 45215	7b. ADDRESS (City, State and ZIP Code) Wright-Patterson AFB, OH 45433-6563
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Aero Propulsion Laboratory 8b. OFFICE SYMBOL (If applicable) AFWAL/POTX	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract No. F33615-83-C-2334
8c. ADDRESS (City, State and ZIP Code) Wright-Patterson AFB, OH 45433-6563	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO.: 61102F PROJECT NO.: 2307 TASK NO.: S1 WORK UNIT NO.: 42
11. TITLE (Include Security Classification) Strain Gage Signal Interpretation	

12. PERSONAL AUTHOR(S)
R. B. Fost, V. C. Gallardo, W. R. Stowell

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final	FROM June 83 TO July 85	February 1986	91

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Strain gage signals from aeromechanical vibrations of rotor blades and vanes have been collected, examined, classified, and generalized in a taxonomic sense. A unified and rational system has been developed for the interpretation of strain gage signals in terms of certain characteristics amenable to computer programming. Included are specifications for both hardware and software.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Robert D. DeRose, Project Engineer	22b. TELEPHONE NUMBER (Include Area Code) 513-255-4163 22c. OFFICE SYMBOL AFWAL/POTX

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

FOREWORD

The research study reported herein was conducted by the General Electric Company under Air Force Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, USAF, Wright-Patterson AFB, Contract F33615-83-C-2334.

This research study was conducted to develop a set of specifications for a computer-directed instrumentation system capable of distinguishing, and subsequently acting upon, the different strain gage signals typically encountered in testing aircraft engine compressors. This report documents the results of this study.

The authors wish to acknowledge the help provided by their colleagues. M. Chalfin and C. Ball of GE's Instrumentation and Data Reduction Operation played back the many tapes of strain gage samples. These were provided by R. McKay of GE's Small Gas Turbine Division in Massachusetts and R. Brady, P. Chifos, B. Dickman, R. Gravitt, P. Niskode', C. Jones, and R. Lovell from Evendale, Ohio. In addition, these colleagues are the experts who provided the knowledge base of the expert system. The help of Sergio Maures for insight of the hardware and software specification is also gratefully acknowledged.

We also wish to thank M.J. Stallone and B. Fister for their technical guidance.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

To safeguard the mechanical integrity of turbomachinery and their components during their development and to assist in determining the aerodynamic-mechanical optimum configuration, the aeromechanical engineer monitors the blading's strain gage signals and assesses their levels with respect to their operating limits. The dynamic strain gages are the means by which the monitor evaluates the mechanical behavior of the compressor or other turbine engine components. His mental alertness, memory of past testing, experiences in strain gage signal interpretation, and the ability for associations, sometimes coupled with intuition, are the qualities an aeromechanical engineer must exercise to avoid mechanical failure of an engine or component. With these skills, some basic data must also be available which include: material fatigue properties, identification of potentially active blade modes and their limiting conditions, resonant frequencies, instrumentation and strain gage sensitivities, and the aerodynamic characteristics such as operating and stall lines as well as choke boundaries.

The simultaneous observation and interpretation of strain gage signals from many blades in several stages of a compressor can be a difficult task for an aeromechanical engineer. This task includes the identification of the type of vibration, their interpretation and assessment of safety level relative to established limits, and also to direct a change in operating condition to avoid failure and/or provide direction for optimizing the aerodynamic performance of the compressor. The essence of this program is to model the thought process of an experienced aeromechanical engineer and allow a computer system to evaluate the existing conditions and make the decisions based on realtime data processing and analysis. The automated system would have the advantage of processing considerably more data than an aeromechanical engineer for on-line interpretation and decision making.

1.1 PROGRAM OBJECTIVES

The overall objective of this work is to ensure mechanical survivability of compressor blading while undergoing instrumented aerodynamic development testing. This differs from other methods in that it will be accomplished by a computer rather than by a human agency. Towards this end, the specific objectives of the research study reported herein were to:

1. Classify the different types of blading vibrations normally obtained from strain gage signals during compressor testing,
2. Establish the characteristics of each type of signal which are different from all other types,
3. Provide specifications for a computer system capable of on-line monitoring and interpretation of compressor blading strain gage signals, and
4. Develop software specifications for this computer system.

1.2 PROGRAM DESCRIPTION

1.2.1 Phase I

Phase I efforts consisted of collecting examples of each different type strain gage signal typically found in compressor testing. These typical signals were extracted from dynamic stress tapes recorded during actual testing of a variety of blading geometries and operating conditions. The different types of signals considered later in detail are: flutter, resonant response, non-resonant response, separated flow vibration, unlatched or misrigged vane, rotor tip rub, stall, surge, and noisy or invalid strain gage signals.

1.2.2 Phase II

Phase II consisted of analyzing the strain gage signals selected in Phase I to determine the distinguishing characteristics of each type of signal. Standard analytical methods - principally the fast Fourier transform (FFT), as well as time domain analyses - were used in the characterization of these dynamic strain gage signals. Hence, this classification methodology is called "dynamic Fourier taxonomy."

1.2.3 Phase III

Phase III required the development of technical specifications for a computer system capable of on-line monitoring and discriminating between the different types of strain gage signals. When conducting such observations, the computer system should be at least as effective as a highly trained aeromechanical engineer. The specified system was developed using modular concepts to permit flexibility.

1.2.4 Phase IV

Phase IV consisted of the development of software descriptions required to program a typical computer that would be used to coordinate the strain gage signal interpretation computer system with the test facility alarm and shutdown controls. The flow of computer operations attempt to follow in logical sequence the procedures normally taken by an aeromechanical engineer.

1.3 SUMMARY OF RESULTS

Strain gage signals from vibrating rotor blades and vanes were collected, examined, classified, and generalized. A unified and rational system was developed for the interpretation of the different signals in terms of certain characteristics amenable to computer programming, see Table 1. The variables found to be most suited for strain gage signal taxonomic classification are obtained by FFT processing of the digitized dynamic strain gage data. Thus this methodology is called dynamic Fourier taxonomy, and the computer instrumentation system capable of monitoring, interpreting, and processing the dynamic strain gage data is called the expert system.

The interpretation of dynamic strain gage signals is, in general, a three-step process:

1. A validity check which determines if the signals are valid or not.

2. A threshold excedence check which compares the signal levels with pre-established safe limits. This requires on-line data analysis to identify the current vibratory modes since strain gage limits are associated with the blading normal modes and operating conditions. Also included here is the selection of operational escape procedure(s) when the stress level(s) and/or the operation conditions are unsafe.

Table 1. Hierarchical Organization of Knowledge Base and Data Processing.

- Knowledge Base
  - Data
    - Pretest Data Must Be "Updateable"
      - Aero Data (Compressor Map)
        - Normal O/L Curve
        - Obj Stall Line "
        - Obj Choke Line "
        - Const. Speed Lines "
          - In Terms Of:
            - • Pressure Ratio
            - • Weight Flow
            - • Corrected Speed
            - • Vane Setting and Schedule
            - • Bleed Rate
      - Scope Limits Data
        - Engine Gage
          - • Location on Blade
          - • Stage ?, Blade ?, Vane ?
          - • Scope Limits: All Modes
            - Stress Versus RPM
            - Campbell Diagram or Frequencies Versus RPM
            - Tolerances on Limits and Modal Frequencies
    - During Test Data
      - Steady State, Slow or Stationary Data Operating Condition
        - Aero Data - Same as Above
        - Toward Stall?
        - Toward Normal O/L?
        - Toward Choke?
        - Mechanical
          - • Vane Setting/Schedule
          - • Bleed Setting
          - • Accel?
          - • Decel?
          - • Rotor Speed
      - Dynamic or Transient Data
        - Rotor Speed
        - Engine Gages Strain Signals
      - FFT or Processed Taxonomic Data (Of Strain Signals)
        - Peak Amplitude
        - Frequency Spectra
        - Campbell diagram or Spectogram
        - Per/Rev Frequency
  - Rules, Heuristics Definitions
    - VIB Identification Characteristics
      - VIB Characteristics Tables
      - Taxonomic Trees
    - Operations on Taxonomic Data
      - Peak Amplitude Versus Time
        - Blossoming
        - Rise Time or
        - Peak/Cycle
        - Modulation
      - Spectra
        - Noise, Valid/Invalid
        - Integer/Noninteger Per/Rev
        - Stress Versus Limits
        - Sudden Reduction in Modal Frequency Can Indicate Crack/Failure
    - Escape Alternatives - In Terms of Operating Conditions: Aero; Vane/Bleed Setting. See VIB Characteristics Table

3. A vibratory response identification which establishes the nature of the vibration and possibly the excitation source, such as resonance, instability, rub, misrigged vane, stall, separated flow, etc. This operation makes use of the above data analyses as well as the entire expert system module's data base contained in the pre-test data and in the "during test data" which is being acquired and updated during the test, see Table 1.

The hardware and software specifications therefore, address both data base and operational logic requirements for the expert system's instrumentation hardware, computer software, and associated data processing capabilities.

2.0 TYPICAL STRAIN GAGE SIGNALS

In collecting sufficient samples of strain gage signals from the extensive General Electric inventory of magnetic tape records to facilitate accurate categorization, an initial finding was the indistinguishability of rotating from stationary strain gage signals. Similar conclusions were also reached when signals from cantilevered, partspan shrouded, and tip shrouded blades were compared. These useful simplifications permitted the removal of these variables from the strain gage signal taxonomy. Hence attention was focused on classifying the different strain gage signals regardless of rotating blade or stationary vane, or fixity.

It should be recognized that most vibratory response events encompass some finite time, which is what an engineer sees when monitoring oscilloscope displays of strain gage signals. However the computer sees the data sequentially, or in serial order. Experience has shown that the frequency spectrum of a strain gage signal is the almost indispensable means for identifying vibration types. However, sometimes the type of vibration cannot be identified without observing the strain gage signal prior to that time (e.g., the occurrence of a misrigged vane or out-of-schedule vane setting) where a Campbell diagram (see Appendix A) may be useful. Thus, to obtain a "pattern" or sufficient temporal samples to allow a frequency spectral analysis, it becomes apparent that on-line computer monitoring of strain gage signals is a relative term which could mean a fraction of a second or several minutes. For example, though frequency spectra require data obtained in milliseconds, Campbell diagrams require a minute or more since they are constructed from data obtained within a rotor speed range, say from idle to design speed.

This part of the report reviews and defines the most significant vibration-types, phenomenologically as well as according to their strain gage signals. This is illustrated with typical strain gage signals, "in real time" as amplitude-time plots, frequency spectrum and/or the more compact Campbell diagram. Included are conditions that produce the various vibration types. The phenomenological descriptions and mechanisms of various vibration types, although documented in References 1 through 4, will be included here for completeness.

2.1 VIBRATION TYPES AND STRAIN GAGE SIGNALS

The vibration types are classified into the following categories:

Forced Vibration

- Nonresonant vibration
- Resonant vibration
- Rotor blade tip rub
- Unlatched or misrigged vane
- Separated flow vibration (SFV)
- Rotating stall
- Pulse type stall and surge

Self-Excited Vibration

- Stall Flutter
- Supersonic Shock Flutter
- Choke Flutter

The malfunctions or noisy instrumentation must also be included:

Invalid or Spurious Signals

- Slipring noise
- Broken (open) or grounded strain gage or lead

The phenomenological descriptions and the typical strain gage signal for these vibration types are given in the following sections.

2.2 FORCED VIBRATION

The structural periodicity of a compressor naturally results in periodic forces and consequently in aeromechanical vibrations. The source of most periodic forces is a circumferential disturbance in the flowfield. Some possibilities are: inlet distortion, rotor blade and stator vane wakes, misrigged or missing vanes, damaged blades, and interstage bleed air extraction. Excitation wakes from the introduction of traverse probes during testing also belong in this category. In a multistage compressor, rotor/stator interaction complicates an already complex loading condition. Because of the rotation and structural periodicity of rotor blades and vanes, the frequencies of these excitations are integer multiples of rotor speed.

Many types of forced vibration response can occur depending on the forcing function, the stage of interest, and the operating regime of the compressor. These types of forced response are described below.

2.2.1 Nonresonant Response

Nonresonant vibration occurs when the airfoil responds to an excitation whose frequency is different from the airfoil's natural frequencies. This is illustrated in Figure 1 where the forced nonresonant response is primarily 1/rev, with the first mode frequency being at least 25 percent higher. The stimulus occurs at an integer multiple of rotor speed since it is created when the blading passes through a flow distortion. In this case it can be seen that as the rotor speed increases, the response grows monotonically and follows the 1/rev line.

2.2.2 Resonant Vibration

Resonant response occurs when the excitation frequency corresponds to one of the airfoil natural frequencies. This is illustrated with the Campbell diagram in Figure 1 where the small nonresonant excitation, following the 3/rev line, coincides with the second flexural mode frequency at about 12,000 rpm.

Since resonant responses occur when an airfoil natural frequency is an integer multiple of rotor speed, expected possible resonances can be determined before the compressor test using the predicted Campbell diagram. Every intersection of blade frequency with an engine order, or per rev line, is a possible resonant point. (Fortunately only a few of these materialize, and usually within tolerable limits.) Since compressor blading has many natural frequencies, several resonances can be encountered at any one rotor speed. When the excitation is from wakes shed from adjacent stages, the excitation frequencies are equal to the rotor speed multiplied by the number of airfoils in that stage (or an integral multiple thereof) and are referred to as passing frequencies. This type of vibration may be encountered by either rotors or stators.

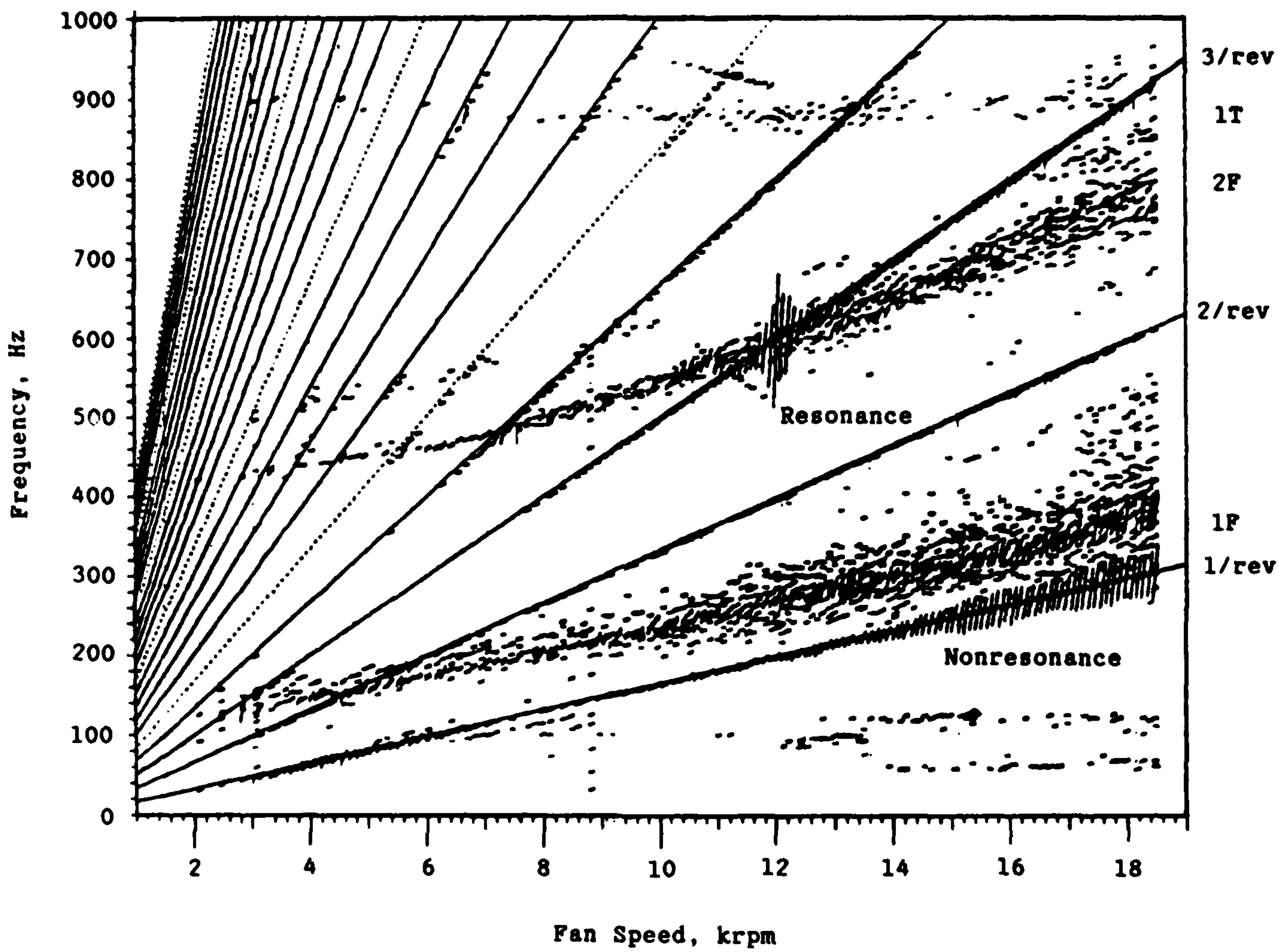


Figure 1. Resonant and Nonresonant Response.

Resonant vibration signal characteristics are best illustrated in a Campbell diagram whose history encompases the times prior to, during, and after the resonant speed. The history prior to resonance shows a rapid increase, or "blossoming" of the signal amplitude as the excitation frequency approaches the blade natural frequency. The history after resonance is perhaps the most important because it shows the rapid decrease of the signal amplitude as the excitation frequency passes the blade natural frequency, and without it one cannot easily differentiate the signal blossoming character between resonance and flutter. (As will be discussed later, flutter usually occurs at non-integer multiples of rotor speed - but nothing in the physics of the problem says that flutter cannot occur at an integral multiple of rotor speed, in which case the signal amplitude would not decrease as the excitation frequency passes the blade natural frequency.)

2.2.3 Rotor Blade Tip Rub

This response is entirely mechanical in nature and almost always involves the rubbing contact of a rotor blade tip with the casing. Normally, the radial clearance between blade tips and the casing is kept small for aerodynamic performance so that rapid acceleration in a relatively cool compressor could permit the rotor to grow faster under centrifugal loading than the casing undergoing expansion with the increasing temperature. Large amplitude blade vibration as well as rotor unbalance response could result in casing contact. Nonconcentricity of the rotor and casing or a slight local bulge of the casing may also cause a blade rub. More than one hit per revolution results from such situations as more than one bulge in the casing, and when the rubbed surface starts coming loose in chunks at more than one location. Engine or casing vibration which is characterized by large relative blade-to-casing radial motion could induce a rub as well. There may be occasions where, due to improper assembly, a casing inner shroud may separate from its base thereby reducing the clearance and resulting in a rub. Axial interference, rare but possible, occurs if blading should become permanently bent, by foreign object ingestion, stall, or some other means, to the point that axial contact is possible. Stall-induced blade vibration, in combination with transient loading during surge, has also been known to reach magnitudes which result in contact with adjacent cascade row.

A strain gage on a rubbed blade has a distinctive time signature that may be described as an initial spike due to the sudden impact followed by damped vibration decay at one (usually) of the blade's natural frequencies, usually a flexural mode, until the blade rubs again and the cycle is repeated. The rate of decay is a function of the blade's damping characteristics. Figure 2a shows a strain gage response at the onset of a single rub. The strain gage waveform in Figure 2b depicts two fully developed rubs separated by about 154^{o} (from Reference 3). Unlike the misrigged vane excitation described below, tip rub does not usually persist since rubbing erodes either the casing material or the blade tip, or both, i.e., the rub is self-limiting.

A unique feature of a blade tip rub is the fact that usually one blade rubs first. That is, due to manufacturing tolerances, one blade is longer than the others (unless the rotor is machined at assembly) and will be the first to encounter the mechanical excitation source. Thus to discern this particular vibration type, the monitor need only check the other strain gage signals from the same blade row during the initial occurrence. However, for minor magnitudes of contact, the initial deflection is sometimes sufficiently low that the triangular envelope is camouflaged by the other types of vibration already present. Therefore careful monitoring, particularly during early phases of testing, is required in order to detect the presence of rubs before they can become dangerously large.

2.2.4 Unlatched or Misrigged Vane

The strain gage signal of a rotor blade behind an unlatched vane is much like a rub but with a somewhat more rounded peak. The dominant excitation frequency is usually one/rev accompanied by an integral order frequency response at a blade natural frequency. The misrigged vane(s) will generally shed wakes much stronger than the other vanes in the stage so that it will be seen as a generator of one/rev stimulus and its harmonics by all the rotor blades. As the vane setting is increased, the wake shed by the misrigged vane becomes stronger and will contain many harmonic components. This is illustrated in the amplitude/speed chart in Figure 3. High frequencies arise from the Fourier components of the spatially narrow circumferential aerodynamic distortion exciting the blade's higher modes. There may be other instances where more than one vane is unlatched; this would make proper

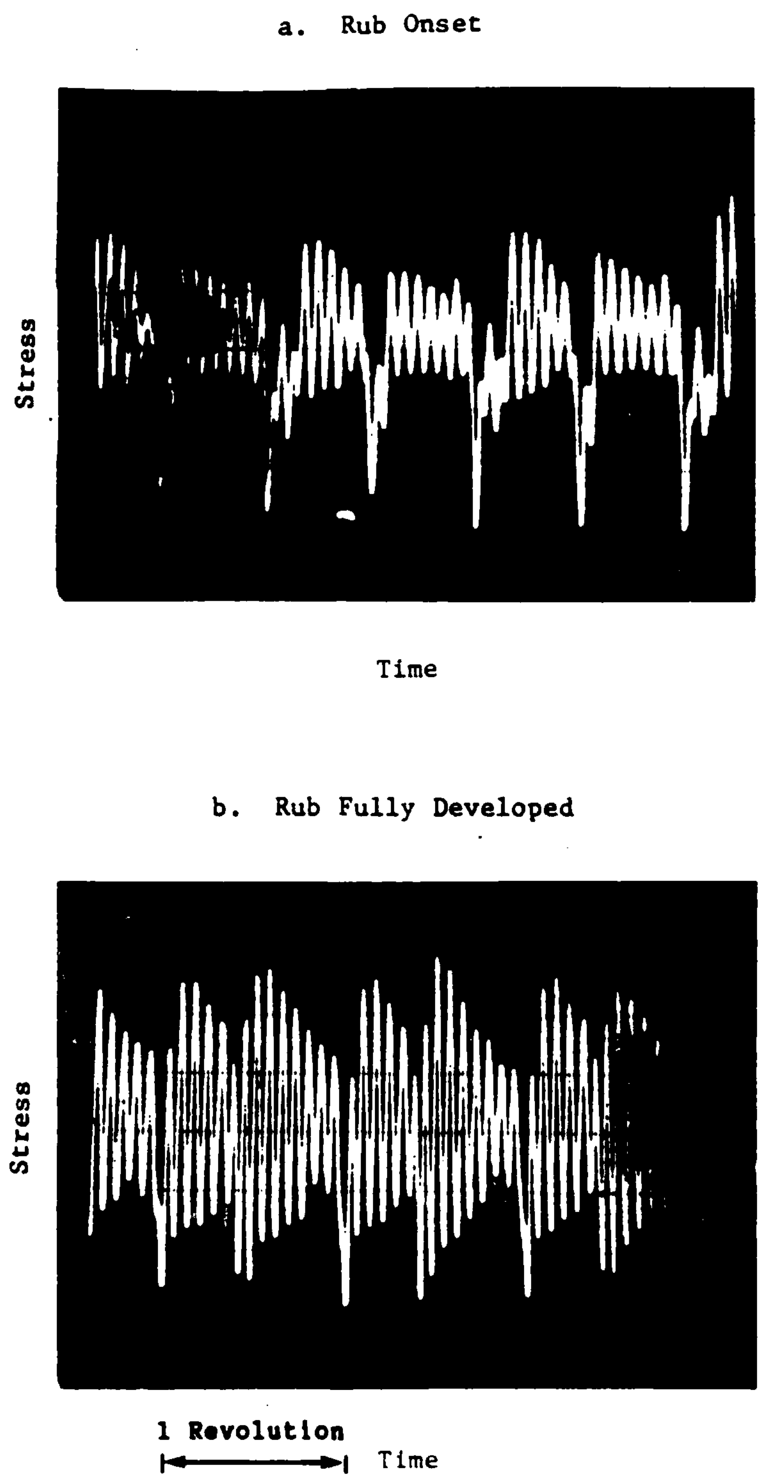


Figure 2. Strain Gage Time Signature During Blade Tip Rub.

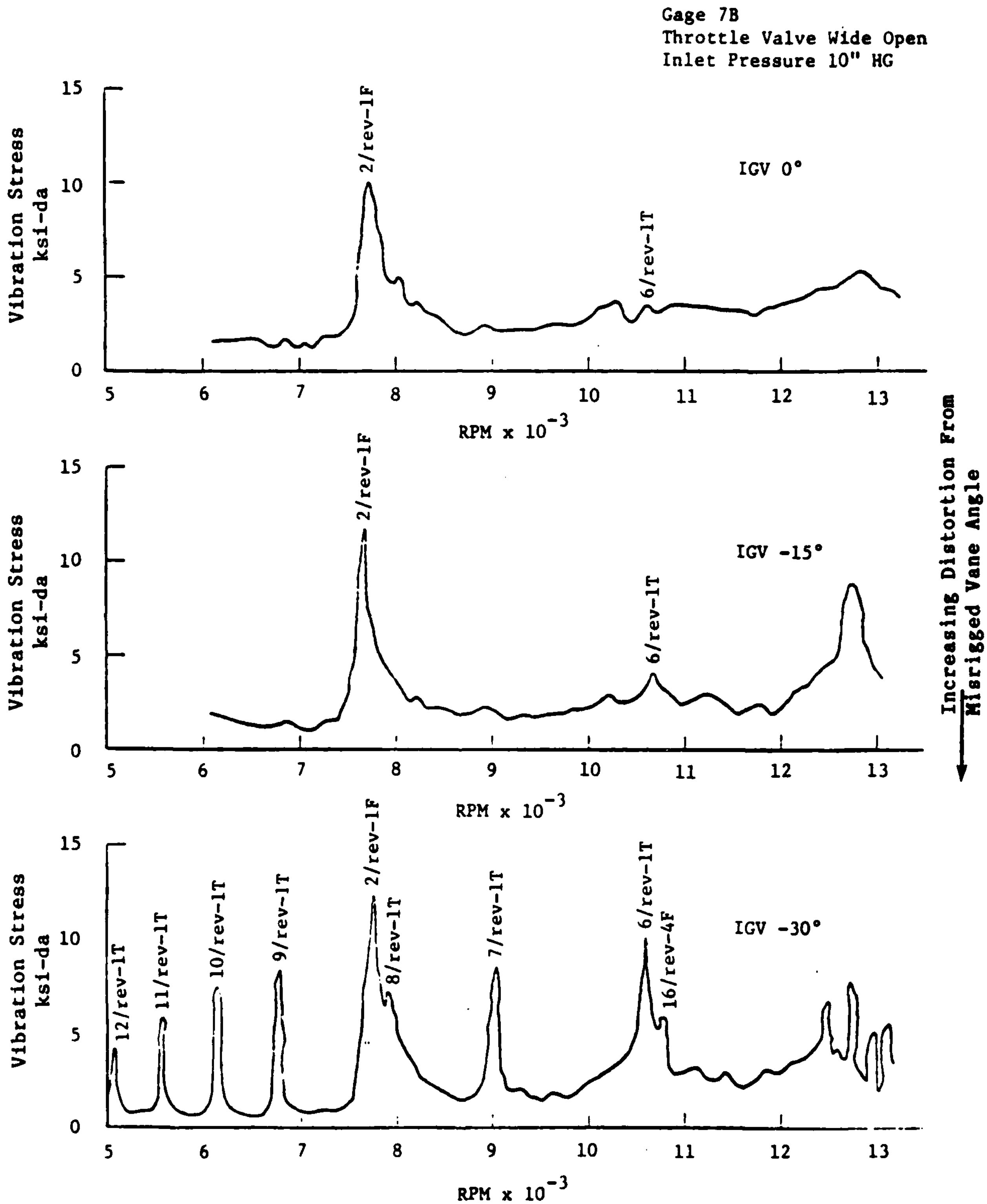


Figure 3. Effect of Single Off-Angle IGV on Rotor Blade Resonant Stress.

identification more difficult. A Campbell diagram representation of the stresses of a rotor blade behind a misrigged vane in the midstage of two different compressors are shown in Figures 4 and 5.

A vane may become misrigged by (1) assembly error, (2) bent vane lever arms from a hard stall, (3) fatigue failure of lever arms, (4) loose vane attachment, and (5) broken vane trunnion. A bird strike or other ingested debris could also result in incorrect vane settings.

Most of the rotor blade response in a stage adjacent to misrigged vanes would be a forced vibration at frequencies of integers of rotor speed with a resonant blossoming at the frequency-integer/rev crossovers. The most reliable way to identify the presence of a misrigged vane excitation is to examine the strain gage signals from all instrumented blades in the stage. They all will be exhibiting the signal characteristics described above.

2.2.5 Separated Flow Vibration

The term separated flow vibration (SFV) is applied to random amplitude response of blading in one or more of their natural vibration modes. This type of response is induced by turbulence, either that existing in the main airflow, or induced on the cascade itself due to high stage loading - either positive or negative directions. Stimuli arise from partial flow separation on the airfoil due to large flow incidences. Usually, response in the lower modes is predominant. The degree of turbulence is indicated by the magnitude of random modulation with time. Accordingly, terminology has been developed relative to percent modulation as shown in Appendix A. Strain gage signal time histories from three blades in SFV are shown in Figure 6.

Occasionally, sudden increases in SFV can be produced by introduction of interstage traverse or aerodynamic probes during development tests. Another consequence of an increasing SFV, such as caused by changing compressor operating conditions, is the possible impending stall and surge, or in some cases, aeromechanical instability. (Instability strain gage samples, presented later in Figures 9 and 10, show SFV before the instability occurs.) In multistage compressors, it may be found that the front stages will encounter high levels of SFV at the low-to-mid speed range, whereas the rear

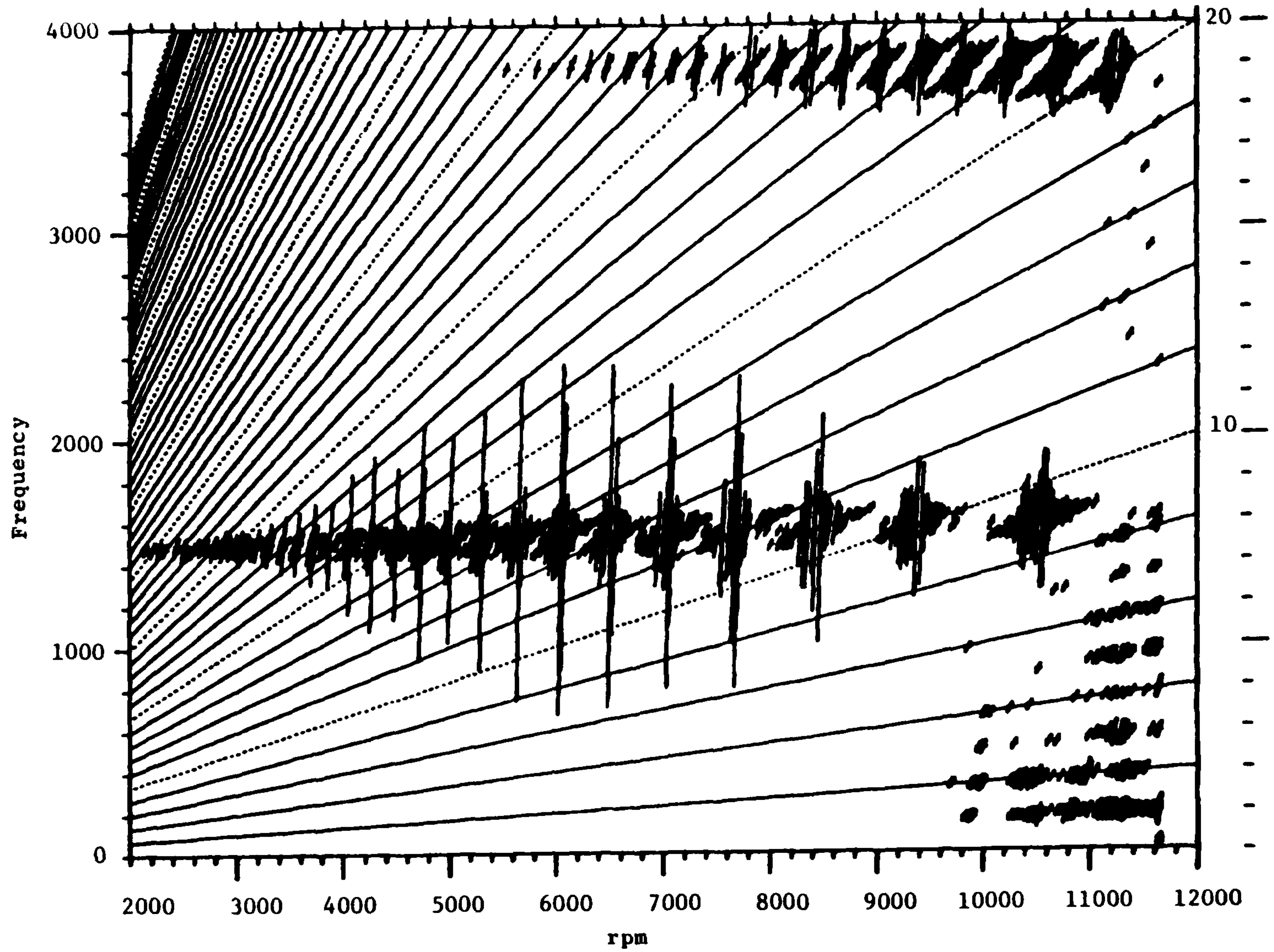


Figure 4. Blade Stress Response to Misrigged Vane.

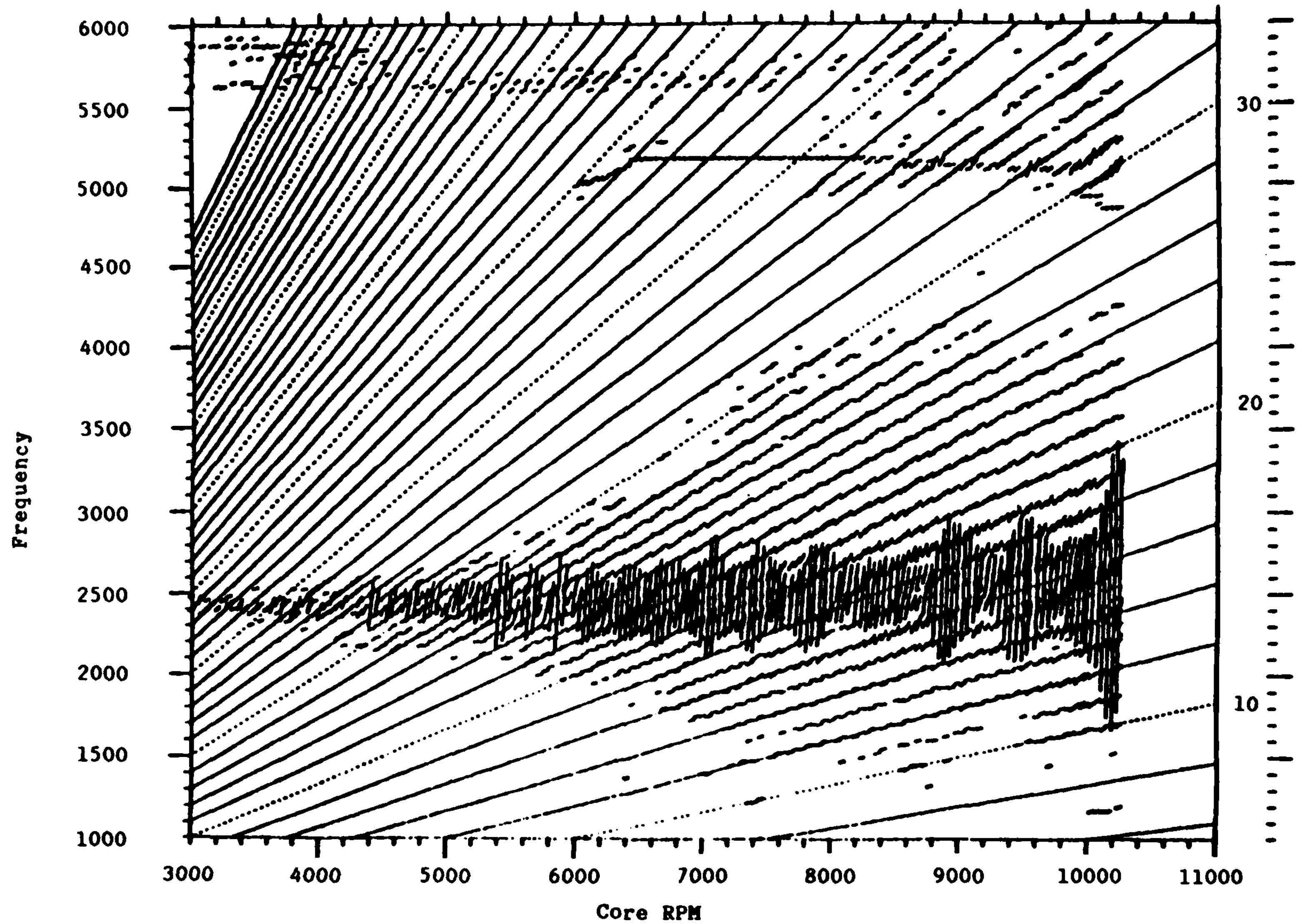


Figure 5. Blade Stress Response to Misrigged Vane.

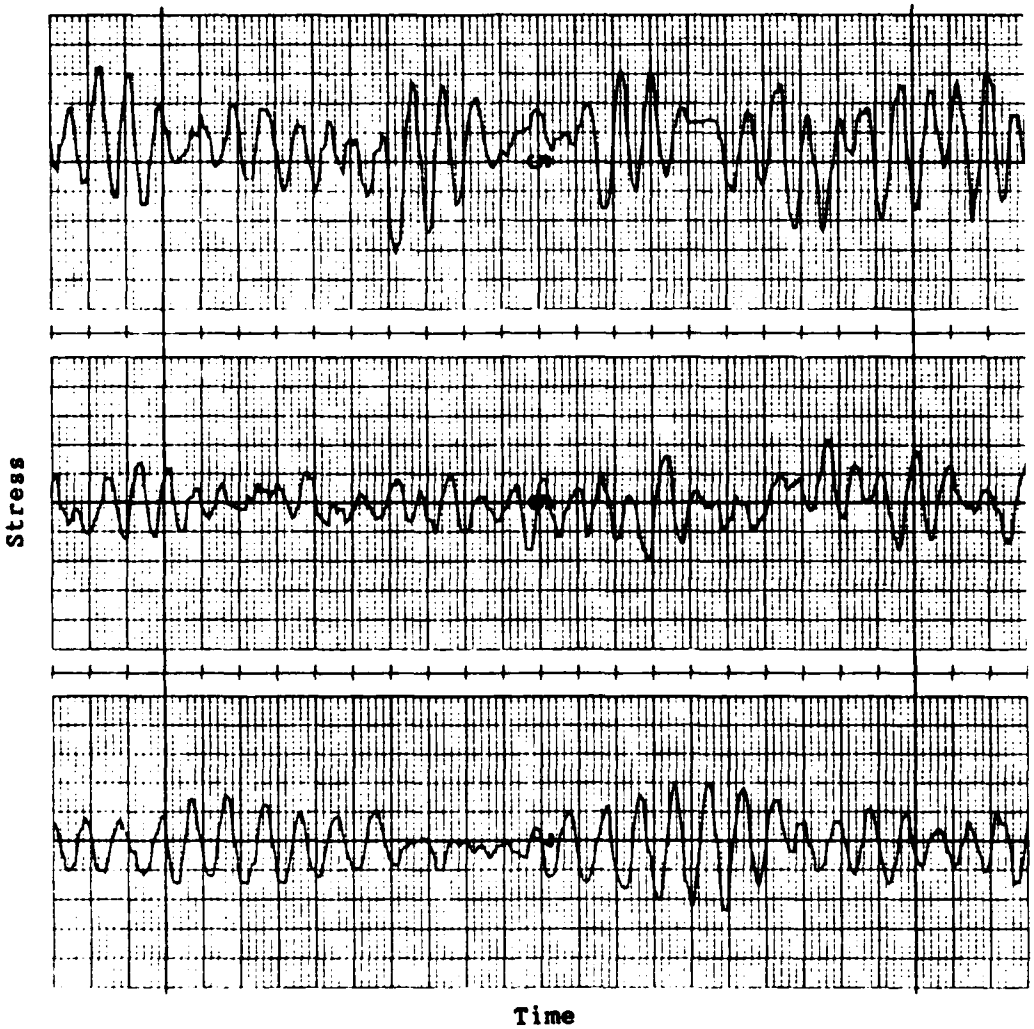


Figure 6. Samples of Strain Gage Signals During SFV.

stages will experience SFV at higher speeds. This is governed by the aerodynamic "matching" in the specific compressor design.

2.2.6 Rotating Stall

This type of stall is characterized by the existence of one or more regions of low airflow in the annulus, with each region rotating in the direction of the rotor at about half speed (actually observed at values between 35 and 65% speed). These low flow regions are called "stall cells." The boundary between good and low flow regions is very sharp, with a sizeable change in cascade loading being experienced by blades and vanes as the edge of the stall cell pass. During severe rotating stall conditions, blade vibration tends to be rather chaotic during the time the blade is immersed in the stall cell. Often this response does not have time to clear up completely between stall cell passings thus masking the stall cell transient, see Figure 7a. When the chaotic blade response does have time to clear, the stall cell encounter is apt to look like a rub as seen in Figure 7b, but the apparent "hits" will occur at approximately 0.5/rev rather than the 1/rev characteristic of a rub. For mild stalls, or for heavily damped structures, the response may largely be limited to the transient load (pivoted stators, and shrouded vanes and blades tend to fall in this category), see Figure 7c.

"Full stalls," which represent the stall line shown on performance maps, occur as full annulus rotating stalls at all speeds for most fans, and for multi-stage compressors in the low-to-mid speed range. Marginally matched compressors can also encounter full rotating stall in the high speed range - usually preceded by a stall pulse (see Section 2.2.7). By "marginally matched," it is implied that the middle stages, whose loading does not change much with pressure ratio at high speeds, are too heavily loaded, and after sustaining full stall, remain stalled as the pressure ratio is lowered. This characteristic occasionally induces the stall to be locked in thus requiring the speed to be reduced to clear the stall. Full rotating stalls typically involve only one cell which extends much of the way through the fan or compressor. The assymetric loading on the rotor during stall is fairly large and usually induces strong engine vibration. This, in combination with excessive engine temperature due to the low through-flow, makes it necessary to clear full rotating stall at high speeds as quickly as possible.

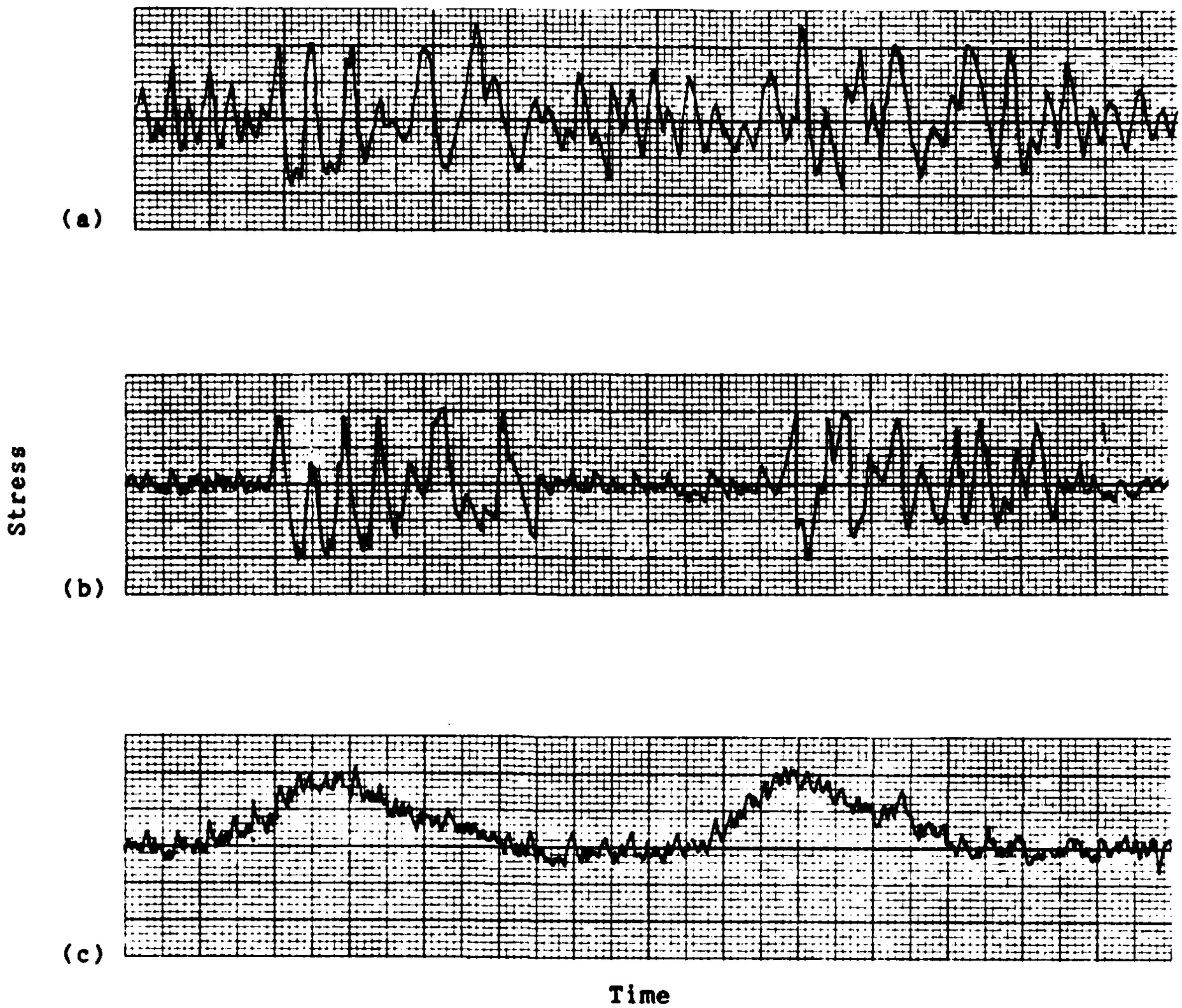


Figure 7. Blade Responses During Rotating Stall.

The front and middle stages usually experience the largest vibratory stresses during rotating stalls, but the stress levels are normally much less severe than for the pulse-type stalls discussed in the next section.

Sometimes full stall will be preceded by local multi-cell rotating stall in some portion of the fan or compressor. It may occur in only one stage or extend through several stages. Those induced near the hub are most easily sensed by cantilevered stator vane vibration, and those near the casing by rotor blades.

2.2.7 Pulse-Type Stall

This type of stall involves complete breakdown of the compressor flow momentarily, the duration of which is controlled primarily by the volumetric characteristics of the portion of the total air induction system affecting the component (Helmholtz resonator effect). The airflow not only stops momentarily, but has frequently been observed to reverse direction during the pulse - this is called surge. This action results in an audible sound similar to a shotgun discharge. Pulse durations have been observed as short as 0.05 - 0.07 second for small compressors to an extreme of 1.5 seconds in a large compressor. This type of stall is self-clearing but will have repeated pulses until some stall-clearing action is taken, such as decreasing the pressure ratio. The short pulses have been observed as rapidly as 11-12 pulses per second. When fatigue damage is a potential problem, such rapid stall pulse occurrences require particularly expeditious stall-clearing procedures. Rotor blade vibration during pulse-type stalls builds up in amplitude very rapidly as the compressor flow breaks down and reduces to normal levels as the flow recovers as shown in Figure 8. Combined aerodynamic and acoustic effects may cause the blade response to rapidly fluctuate during the pulse. Stator vane response, on the other hand, tends to be strongest during the periods of flow breakdown (early in the pulse) and flow re-establishment (late in the pulse).

Pulse-type stall is indicative of instigation by migrating stages, i.e., stages whose loading increases appreciably with increasing pressure ratio at a given speed. The sudden pressure ratio decrease during the stall reduces the loading on these stages thus tending to clear the stall. In the high speed range, these migrating stages would be the rear ones, extending further forward into the middle stages in the mid-speed range (75-80% speed).

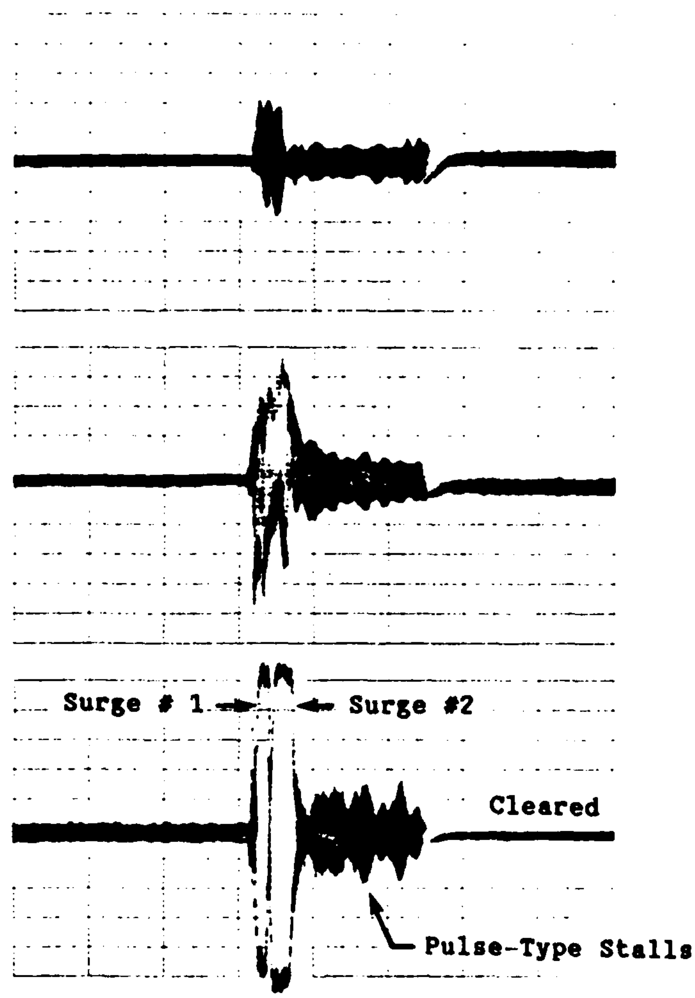


Figure 8. Pulse-Type Stalls and Surge in a Multi-Stage Compressor.

Pulse-type stalls are rarely experienced below 70-75% speed. As the foregoing implies, pulse-type stalls do not occur on single stage fans, and rarely on two-stage machines. Generally four or more stages are needed before expecting pulse stalls in the high speed range. Pulse stalls on two or three stage machines imply virtually identical stage loading for the stages at stall, thus more readily allowing complete flow breakdown to occur.

Pulse-type stalls produce much higher stress levels than do full rotating stalls. Moreover, maximum response is usually experienced in the mid-stage sections, with the forward and aft stages rarely exceeding safety limits. The stress signals are characterized primarily by modulated amplitude response of the first flexural or first torsional modes, or both. Preceeding stall, the level of SFV usually increases, so that SFV can be an indicator of imminent stall. Stall vibration is a forced response at the blade's natural frequencies which are independent of rotor speed.

2.3 SELF-EXCITED VIBRATION OR FLUTTER

Aeroelastic instability, or flutter, of blading is a self-excited vibration condition where the aerodynamic loading which sustains the motion is induced by the motion itself. Upon entering the instability, there may be some preliminary small bursts of stress followed by a rapid buildup of stress to a stabilized amplitude, which may be appreciably in excess of scope limits. This amplitude will remain fairly constant until the operating conditions are changed. This characteristics has led to the use of the term "limit-cycle" instability to describe the phenomenon. Blade response is generally in either first flexural or first torsional modes, but instances of second flexural mode instability also have been encountered. Multiple mode instabilities are rare but have been observed. The onset of an instability condition is normally characterized by a very modulated stress signal with several frequencies (SFV). Then the bursts and rapid buildup of stress are dominated by the flutter mode, so the response is almost a pure sinusoid at the blade's natural frequency which is independent of rotor speed.

Figure 9 is a composite of strain gage signals on a blade obtained at different speeds that is encountering instability. One can see how the amplitude increases as the destabilizing condition is reached and how the

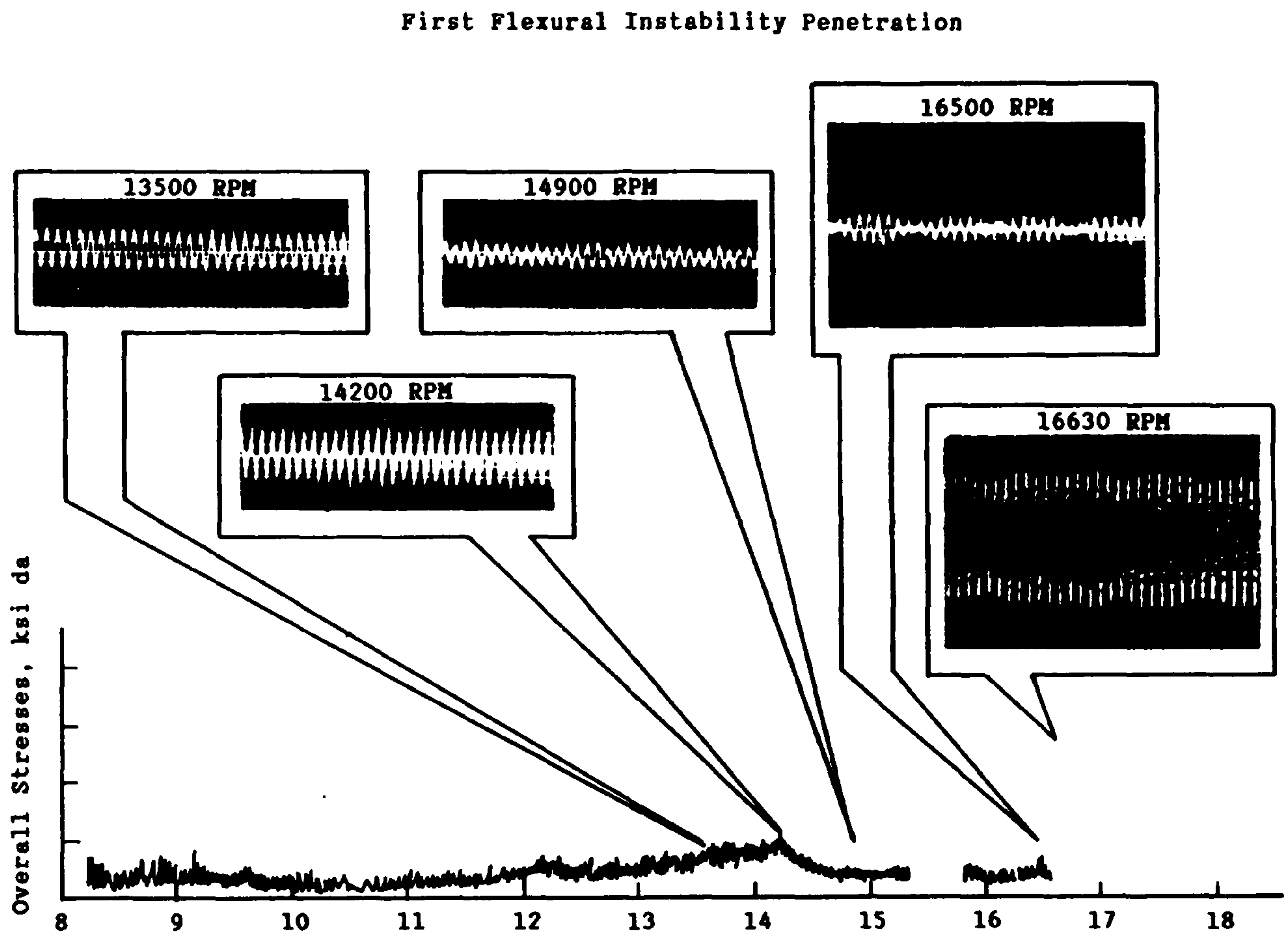


Figure 9. Blade Aeromechanical Instability.

frequency becomes 'pure' and amplitude becomes constant and large. Figure 10 is the result of a frequency analysis during a throttle to torsional stall flutter. Here, one can see that before the instability is developed, the frequency content is made up of several modes, whereas at full instability, the vibration is at one frequency which is a noninteger multiple of the rotor speed.

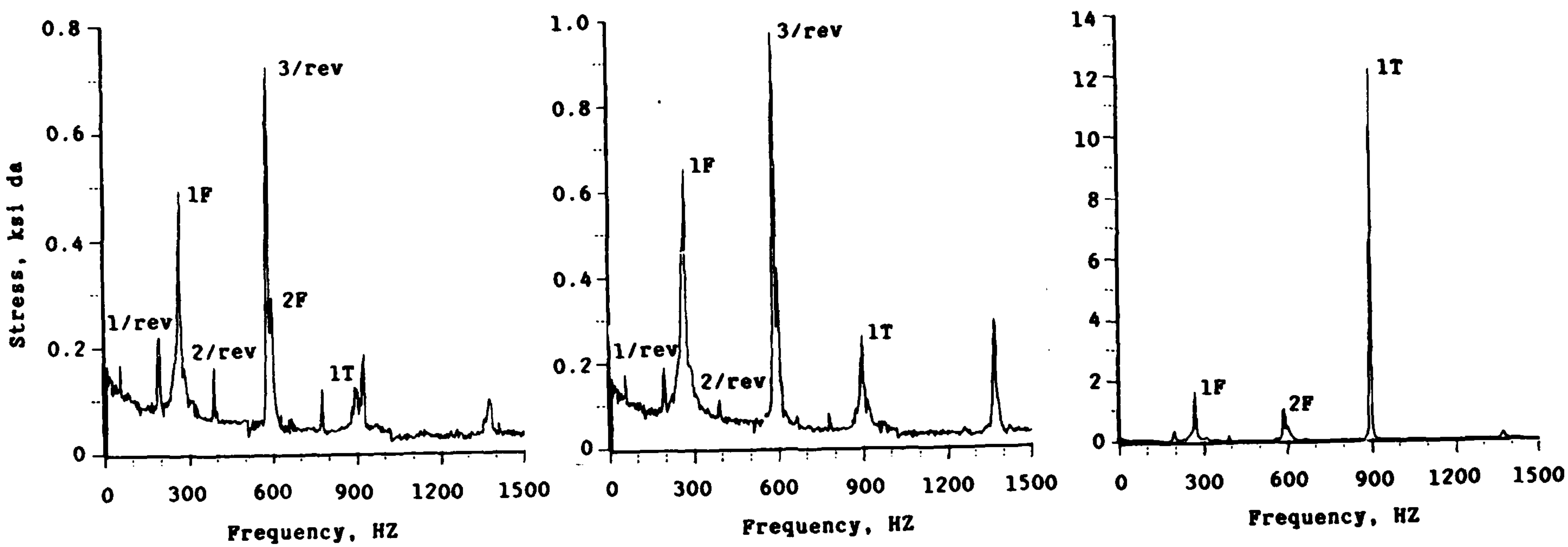
Instability may be encountered in a few blades in a stage or it may be a system instability wherein all the blades in the cascade vibrate at the same frequency and at a constant interblade phase angle but not at the same amplitude. This is due to blade mistuning. There are various types of flutter encountered in a typical compressor which include stall flutter, choke flutter, and supersonic shock flutter. Their location on a typical compressor map are shown in Figure 11 and their characteristics are described in detail below. Despite occurrences at different Mach number and flow regimes, the strain gage signals of the three types of flutter are very similar. They are differentiated from one another by the location on the operating map where they occur.

2.3.1 Stall Flutter

Flutter experienced at high stage loading (as in a highly throttled stage) and at relatively low to transonic speeds is usually characterized by a torsional mode response. This type is known as subsonic stall flutter. Supersonic stall flutter occurs at highly throttled conditions and at transonic to supersonic speeds and is usually characterized by a flexural mode response. These are positive incidence type phenomenon sensitive to stage loading, stage inlet pressure, and temperature and pressure ratio.

2.3.2 Supersonic Shock Flutter

Supersonic shock or inviscid flow flutter is pressure ratio dependent and occurs at supersonic speeds in the vicinity of the nominal operating line. These have been experienced in the development of high performance compressors. Generally, this type of flutter occurs in the first torsional mode and precipitates at or near zero incidence angle.



a. Nominal Operating Line

b. Intermediate Operating Line

c. Instability Boundary

Figure 10. Frequency Analysis During a Throttle to Torsional Stall Flutter.

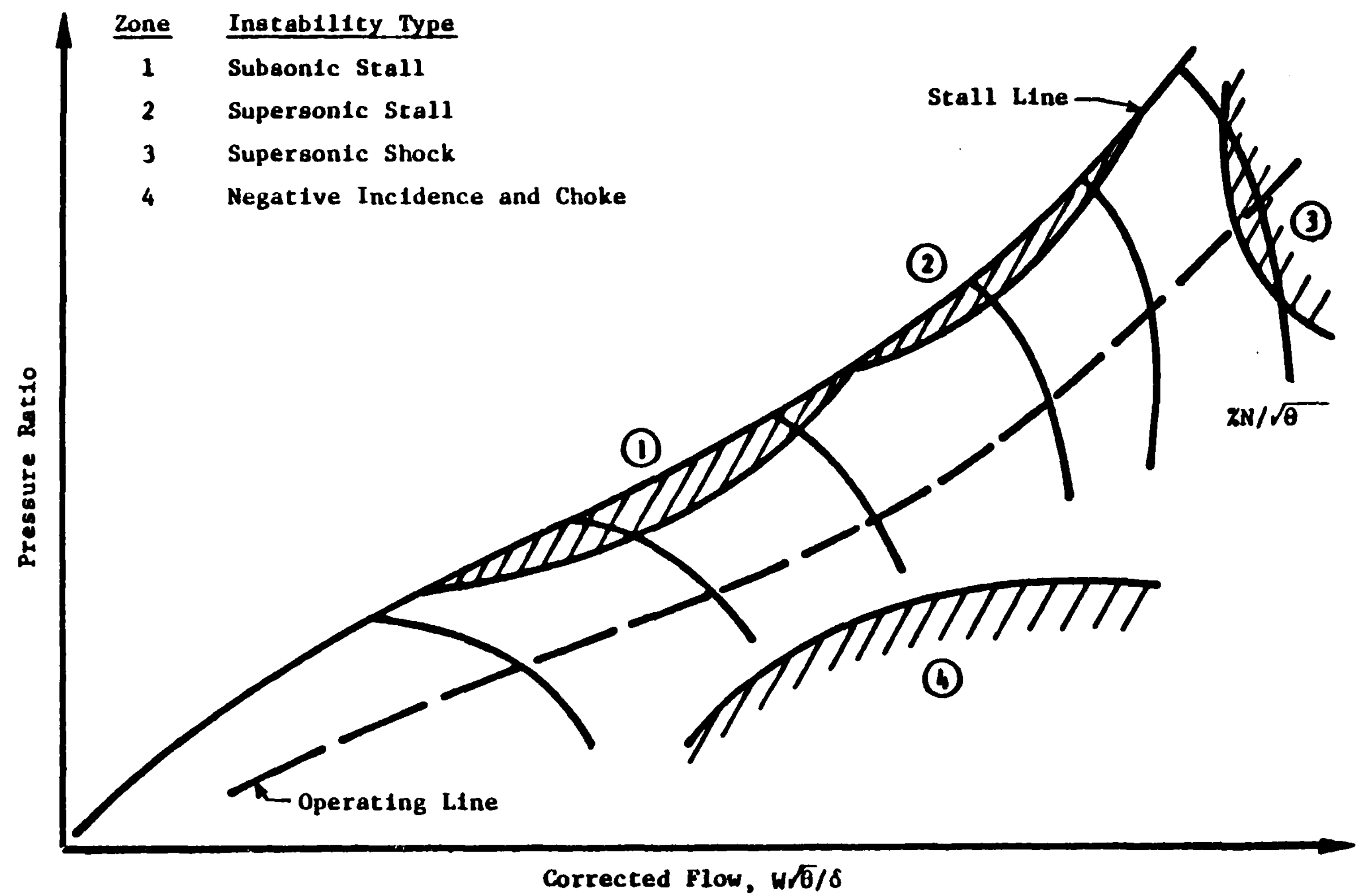


Figure 11. Typical Performance Map With Blade Flutter Zones.

2.3.3 Choke Flutter

Flutter which occurs at negative incidence and a low pressure ratio is called choke flutter. Choke flutter has been experienced at subsonic, transonic, and supersonic speeds and can manifest itself in first flexural, first torsional, or second flexural mode. This type of flutter usually occurs in the mid-stages of a compressor, especially when variable stator rows are involved.

2.4 INVALID OR SPURIOUS SIGNALS

Signal interpretation can be made more difficult with the presence of erroneous signals from strain gages, electronic conditioning equipment, and slipring or telemetry systems. The identification of bad strain gage signals has two basic goals:

- To preclude recording erroneous and misleading stress data,
- To alert the aeromechanics monitor to the need for remedial action.

Accordingly, Table 2 delineates typical bad stress signals, their potential causes, checks to be made, and possible remedial actions.

2.4.1 Anomalies in Slipring and Telemetry Signals

The stresses in rotating blades are measured by strain gages whose signal are transmitted to the stationary oscilloscope displays and magnetic tape recorders. To "jump the gap" from rotating sensors to fixed receivers, the strain gage signals are transmitted through multichannel sliprings. Dirt, moisture, or defects in the contacts of the slipring result in erroneous signals quite different from noisy strain gages, see Figures 12 and 13.

Another means to transmit rotating strain gage signals is through the use of a telemetry system. Analogous to radio broadcasting, the strain signals are broadcast by a transmitter rotating with the rotor and received by a stationary antenna which relays the signals to the recording and display center. One-sided noise may be induced into the telemetry system from either nearby electronic systems in the test cell or from a local FM radio station.

Table 2. Invalid Strain Gage Signals

Symptoms	Possible Causes(s)	Remedial Action
Noise at 1/Rev usually on one side of signal	Slipring Noise.	• Clean, or replace, slipring if noise persists.
Noise spikes at 1/Rev on one side of signal.	Slipring Noise	• Same as for more severe noise case (shown above).
Constant noise on side of signal. (See Fig. 13.)	Partially grounded circuit, or slipring noise.	• Try reversing polarity of power supply - sometimes helps signal of grounded gages. • Clean, or replace, slipring. • Look for grounded exposed wires, plugs, or connections.
All noise.	Grounded, shorted, or open circuit which has intermittent grounding or shorting too.	• Check for crosstalk from a bad gage. • Check for broken or damaged leads. • Check for slipring problems if several signals are lost in rapid succession.
Signal visible through noise.	Crosstalk from bad gage in another circuit.	• Turn off power to bad gage, and ground its circuit if needed.
Signal interrupted by noise frequently.	Intermittent ground or short.	• Check for damaged leads, and loose plugs or connections.
Occasional loss of signal.	Intermittent opening or shorting.	• Check for broken wires in accessible areas. • Check slipring circuit, plugs and connections for possible intermittency.
Spikes on one side of signal.	Gage coming unbonded from blade or grid becoming overstressed (yielding) during tension portion of vibration.	• Invalid signal - turn it off.
No signal.	Open circuit. Power not turned on, malfunctioning amplifier, scope circuit, or other electronic problem.	• Check for broken wires or connections. • Check slipring for open circuit. • Make sure all electronic switches are in proper positions. • Check amplifier, scope, etc. for malfunction - possiblly put gage signal in another channel as a check.

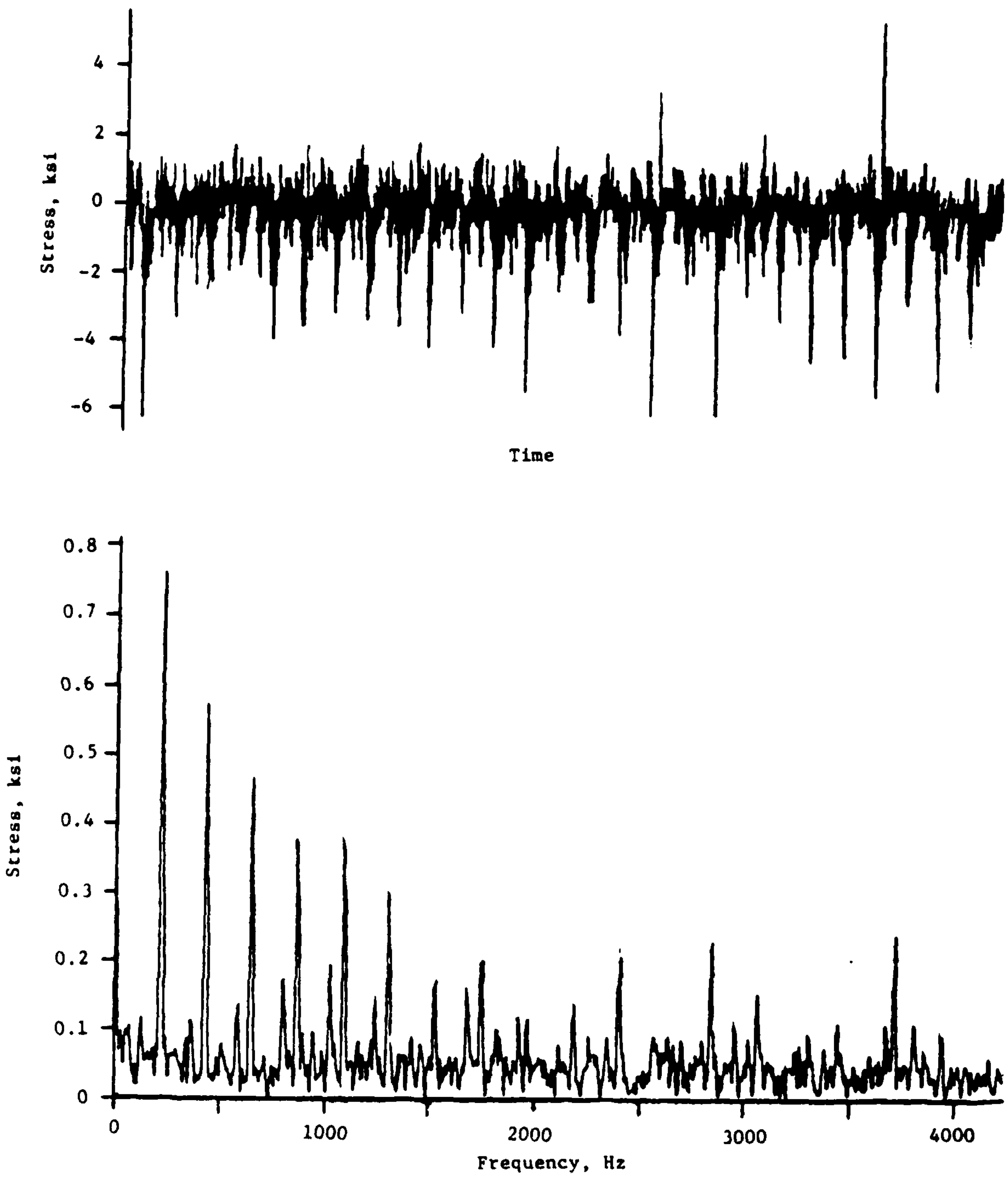


Figure 12. Noisy Strain Gage.

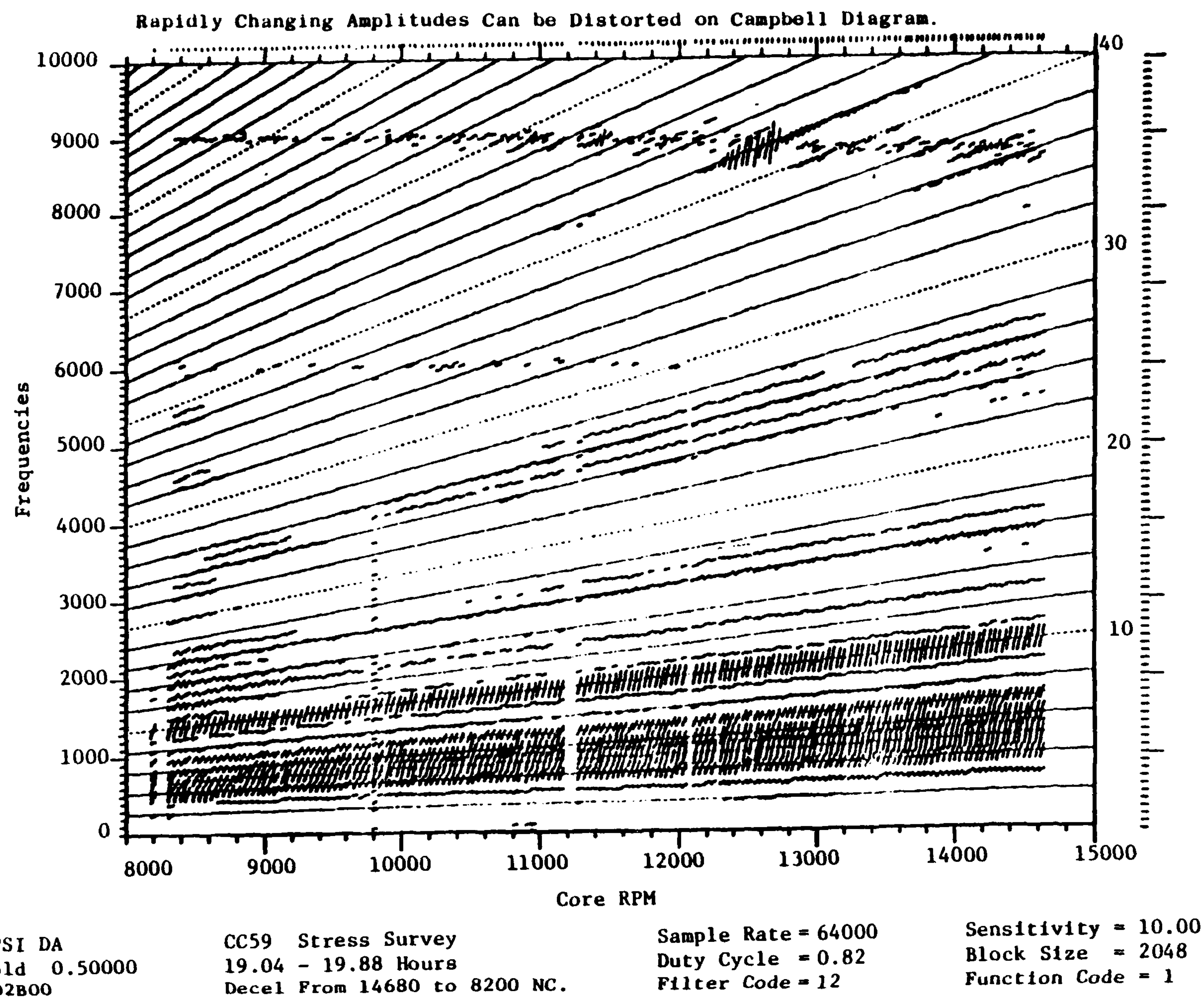


Figure 13. Campbell Diagram of Strain Gage Signal with Slipring Noise.

Also, a transmitter can fail and shift into an adjacent carrier frequency, causing cross-talk induced white noise on both signals.

2.5 TAXONOMY OF VIBRATORY STRAIN GAGE SIGNALS

The foregoing presented the significant vibration types that are normally exhibited by compressor blades and vanes during development testing. Their descriptions as given in this section are partly phenomenological, that is by the physics and mechanisms of cause and effect, and partly by the characteristics of the strain gage data in the form of history or frequency spectra. These examples of the strain gage signals are typical of compressor blading whether rotor blades or stator vanes and regardless of fixity or support conditions. Only by a close examination of the resonances in their Campbell diagrams can one find any distinction between blades and vanes; blade resonant frequencies show an increase with rotor speed. However, this is not always true because high speeds raise material temperature which tend to flatten or even lower this curve. This is especially true at the last stages of a high pressure ratio compressor.

Hence, the elimination of conditions of fixity or rotating vs. stationary blading simplifies, and also unifies, the taxonomy that will be developed in the next section. But the importance that environmental or operating conditions play in the interpretation of strain signals offsets this simplification. In addition to the high frequency vibratory strain gage data, the almost static steady state aerodynamic condition of the compressor must be included. This magnifies the range of variables and their signature in the time and the frequency domain, and the diversity of instrumentation, hardware, and software that are required for sensing, processing, and interpretation.

3.0 STRAIN GAGE SIGNAL ANALYSIS AND CLASSIFICATION

As previously stated, one of the program objectives was to establish the characteristics of each type of strain gage signal which are unique from all other types. The means to this end were to analyze each of the typical signals presented in the preceeding chapter using FFT analyses.

Classification requires fundamental units which are indigenous to the body of data and it is on these units that classifying criteria are established. The taxonomy in various fields has been reviewed to find some insight applicable to strain gage signals. Unlike these disciplines, strain signals are dynamic so that their signatures are not static but change rapidly in time. So a system must be developed which is applicable to dynamic data to identify not only the taxonomic variables or parameters, but also their form. The strain gage analog signal is a dynamic history of stress (voltage) amplitude in time. This amplitude time history, or the waveform, can be digitized so that it can be processed using the FFT. Such processing can yield different forms of the basic stress data. These include the frequency spectrum, cross-spectrum, Campbell diagram, and amplitude-phase frequency plot. These "variable forms" are the taxonomic variables and are no longer the one-dimensional kind but rather consist of at least two dimensions. For example, a frequency spectrum is a two-dimensional or two parameter variable of amplitude and frequency, whereas a Campbell diagram involves the added dimension of rotor speed.

Various taxonomic variables have been examined to determine the optimal data representation - keeping in mind the necessity for the fewest variables and simplest representation so as to minimize the requirements for hardware and software systems in a computer implementation of the strain gage signal interpretation. Following classical taxonomy in natural history, analogues of the hierarchic orders have been identified for strain gage signals. The actual logical classification itself is found to correspond to a branch of artificial intelligence called "expert systems." The latter is the natural consequence of computer implementation of the logical and deterministic steps a human expert may employ to identify phenomena in his/her field of experience.

3.1 DYNAMIC FOURIER TAXONOMY

Dynamic Fourier taxonomy is the application of the FFT for the purpose of identification and interpretation of temporal dynamic data. The FFT transforms a collection of transitory dynamic data into stationary data that can be more easily correlated and identified. Though "on-line" vibration identification is the obvious objective, the reality of the computer examining a collection of the data within some small but finite time must be acknowledged.

The results of FFT analyses of time series data include:

- Frequency spectrum
- Campbell diagram
- Auto- and cross-spectrum
- Spectogram (similar to a Campbell diagram, except the frequency distribution is with respect to time)
- Phase-frequency plots
- Cyclic or harmonic averaging (separating synchronous from nonsynchronous response)

These various output capabilities of the FFT can provide much information about dynamic data, but here the need is to limit to as few as possible thenumber of FFT-determined variables. Moreover, to further minimize the time required for vibration identification, the FFT processing time must be short. This is requisite in meeting the objective of an "on-line" near real time vibration identification system that can quickly diagnose and then escape from an unsafe operation condition before failure or damage can occur.

3.1.1 Taxonomic Variables

Using taxonomic variables reduces the voluminous time series strain gage data to a few parameters. The fewer the variables, the fewer the criteria required to evaluate the data. Experience in monitoring compressor tests and in analyzing dynamic strain gage signals dictates the following taxonomic variables as the minimum required:

Peak amplitude time-series
Frequency spectrum
Campbell diagram

The peak amplitude time-series is obtained as the dynamic strain gage data is being digitized. This is key in determining the validity of the signal and for triggering alarm/escape procedures due to high stress conditions which may have been encountered. This time-series also is fundamental for interpreting signals with unique shapes, e.g., a tip rub or a misrigged vane.

The frequency spectrum provides the frequency content of the signal and the associated stress amplitude at each frequency. This allows identification of the active vibratory modes of the blading in the data segment and, knowing the rotor speed, immediately identifies those frequencies which are resonances, i.e., integral multiples of rotor speed.

The Campbell diagram, a history of the frequency and stress amplitude response over a range of increasing or decreasing rotor speeds, permits identification of vibration types which are best characterized in this manner, e.g., a resonance or a misrigged vane.

The behavior of the strain signal in terms of the peak amplitude and the frequency content (relative to rotor speed) are fundamental for vibration identification. The three taxonomic variables described above provide the means to interpret such behavior relative to vibration types, and with stress limits, assess the safety of the stress levels.

Occasionally a frequency spectra or Campbell diagram is sufficient to identify the vibration type from the strain gage signal. In other cases, the vibration type can be more easily identified by a time series. However, both spectra and time series may be necessary for an unambiguous determination.

In the samples of the preceding chapter, the various vibration types have characteristic time series data and frequency spectra. However, to these one must include the frequencies as multiples of rotor speed. Either taxonomic variable has certain properties that describe its "shape in space" e.g. in a two-parameter plot representation.

3.1.2 Quantitative Values of Taxonomic Criteria

In describing the characteristics of the spectra and time series data of the various vibrations, qualifications were made on frequencies and the shape of the amplitude-history. These qualifications indicate both the abstraction of certain geometric characteristics and its quantification such as the notions and measures of an "integer or noninteger" multiple of rotor speed, "amplitude modulation," and others.

These qualifications and their mathematical or geometric abstractions are the means to generalize the essence of the vibration types and provide the medium for their hierarchical classification, and their numerical values can serve both to rank them and to delineate one kind of vibration from another. Thus we have the basis for a taxonomic tree and quantitative classification criteria.

Contained in the glossary of Appendix A are terms for the dynamic Fourier taxonomy of vibratory strain gage signals - descriptive, relational, and numerical. Some of these concepts can be found in tests on analysis of random data, e.g., Reference 5.

3.2 VIBRATION STRAIN SIGNALS IDENTIFICATION; THE EXPERT SYSTEM

Application of dynamic Fourier taxonomy for both the abstraction of essential vibration characteristics and the logical identification of strain signals is best performed by the taxonomic system practiced in allied fields. Implementation by computer is called the "expert system," a relatively new and rapidly developing field in artificial intelligence.

An expert system is a logical simulation of the rules, data, rules of thumb and reasoning that a human expert exercises. These programs are typically written in non-FORTRAN languages because expert systems do not deal with the voluminous numerical data normally encountered in engineering analysis but are logic or decision intensive. One of these is the LISP language currently employed in the latest expert programs. For example, given a list of random integers with the range from 1 to 100,000, one wants to find how many times 8787 occurs in the set. Conventional programs would "look" at all the numbers. An expert system program would have a means to skip numbers that are obviously far from 8787, e.g., it will ignore all numbers of three or fewer digits and numbers of five digits and greater.

To formulate strain gage signal identification, expert system methodology is followed. The method consists of two parts:

1) The knowledge base which includes definitions, data, and rules of thumb or heuristics, and
2) Inference structure which is the logical or reasoning process.

As depicted in Table 1, the knowledge base for this application contains the strain gage signals (time series data), the taxonomic variables of the signals (determined by FFT), the compressor operating conditions, the characteristic properties of the various vibration types, limiting conditions, modal frequencies - in short, all the physical data pertinent to the compressor blading and its strain gage signals. The inference structure is the logic one uses to operate on the knowledge base to identify the strain gage signal. An example of this inference structure is the fault or taxonomic tree or the semantic network. The element of such a network may be a simple syllogism. The latter is made up of three statements: a major premise or a general proposition, a minor premise, and a conclusion. An example is the following:

- All even integers are divisible by 2 (major)
- 986 is divisible by 2 (minor)
- Therefore 986 is an even number (conclusion).

One proceeds from one branch of the taxonomic tree or a node in the semantic network to another until one can go no further.

The following sections describe the essential characteristics of the various strain gage signal types in terms of modification of their indigenous parameters (history, frequency, amplitude) and their taxonomic forms (FFT calculated spectrum, Campell diagram). Because it is important to have the signal characteristics and operating conditions prior to the time of interest, these are given in the following tables as two columns of events: prior to and during the event of interest. Included are conditions for the onset of the vibration and the operational escape procedure when the strain levels are unsafe.

These tables are the fundamental knowledge base which may then be ordered into an inference structure. The inference structure presented here is a taxonomic or fault tree. This tree is the barest summary of the strain signal characteristics contained in the knowledge base. In actual computer programming, both taxonomic tree and tables of the knowledge base must be used together.

3.2.1 Knowledge Base Tables

Table 3 contains descriptions of the essential characteristics of the strain gage signals of blading vibration.

3.2.2 Taxonomic Trees

The taxonomic trees in Figures 14, 15, and 16 are inferred from Table 1 and contain the inference structure of the strain gage signal identification expert system. Periodicity, integer or noninteger frequencies and others are the hierarchic elements associated in classical taxonomy.

3.3 ESCAPE ALTERNATIVES

3.3.1 Operational Variables

The operating conditions is the environment of the compressor. These conditions are measures of the pertinent properties of the environment, or more specifically, the aerodynamic, thermodynamic and mechanical characteristics of the vehicle and the air around it. Changes in the environmental properties bring about corresponding changes in compressor performance and loading and hence, similar effects on blade vane strain gage response.

For compressor and test facility, these operating conditions are the steady and static properties of vehicle and atmosphere. These are normally

Table 3. Knowledge Base Tables.

(a) RESONANCE

Prior to Event	Item	During the Event
Low stress, sometimes modulated.	Signal characteristics	High stress with little modulation, blossoming at frequency-per rev crossing and decreasing after the crossing.
One or more modes. Dominant frequency may follow per rev line near resonant frequency.	Frequency characteristics	One dominant mode usually. Two or more possible. Dominant mode follows per rev near resonant frequency.

Onset	Operation	Escape
Accel. or decel.		Change speed
Crosswind/distortion		Reduce inlet distortion
Vane setting		Change vane setting
Open/close bleed		Open/close bleed

Remarks

Noticeable in speed changes.

(b) NONRESONANCE

Prior to Event	Item	During the Event
Low stress, sometimes modulated.	Signal characteristics	Amplitude grows with increasing speed; no b[illegible]soming except at res[illegible] condition. Low modulation.
Several frequencies but with one or more dominant frequencies following per rev lines.	Frequency characteristics	One or more frequencies at an integer per rev. Blade natural frequencies are removed from per rev lines.

Onset	Operation	Escape
Accel		Reduce speed
Distortion		Reduce distortion
Vane setting		Change vane setting
Open/close bleed		Open/close bleed

Remarks

Amplitude increases normally with accel - unless at a resonance.

Table 3. Knowledge Base Tables (Continued).

(c) SEPARATED FLOW VIBRATION (SFV)

Prior to Event	Item	During the Event
Low stress, little or modulation.	Signal characteristics	High stress, high modulation.
One to several modes. Frequencies can be non-integer and integer.	Frequency characteristics	Several frequencies. Non-integer per rev. Non-periodic, non-resonance modes are 1F, 1T, and 2F. Higher modes possible.

Onset	Operation	Escape
Increase back pressure Decrease/increase speed Inter-stage mismatch Vane/bleed operation Radial distortion		Decrease back pressure Speed change Vane/bleed operation

Remarks

From accel. at idle to max. speed, LP blading usually encounters SFV at the low speeds then diminishes. The HP normally encounters SFV at the higher speeds. This is due to inter-stage aerodynamic matching.

(d) INSTABILITY

Prior to Event	Item	During the Event
Low to medium. Modulated. Stress modulation increases towards instability.	Signal characteristics	Medium to high stress. Modulation decreases, may vanish. Signal tends to a clean sinusoid with near constant amplitude.
Variable frequency content towards instability. Low and high frequency modes co-exist interchangeably.	Frequency characteristics	One frequency usually dominates, usually 1F, 1T or 2F. (More than one flutter mode are possible.) Frequency is usually non-integer.

Onset	Operation	Escape
Stall Flutter Increasing back pressure Increasing speed Increasing incidence		Stall Flutter Decrease back pressure Reduce speed Decrease incidence
Choke Flutter Decreasing back pressure Decreasing incidence		Choke Flutter Increase back pressure Increase incidence

Remarks

Choke flutter occasionally occurs in outlet guide vanes also.

Table 3. Knowledge Base Tables (Continued).

(e) RUB

Prior to Event	Item	During the Event
Normal	Signal characteristics	High stress. Spikes that rise very steeply and dampen quickly, then repeat. Look like Christmas trees.
Other types of vibration	Frequency	Large 1/rev with usually 1F mode. Fully developed with 1F blossoming at per revs during an accel.

Onset	Operation	Escape
Break in of new compressor Tight clearances Stalls Rapid accel/decel Casing vibration Rotor vibration Bodie burst or stopcock		Reduce speed slowly Clear stall Shut down - examine - fix Increase rotor casing clearance Preventative: slow accel/decel. For compressor with tight clearances.

Remarks

May be self clearing by wearing out casing liner and/or blade tips.

(f) MISRIGGED VANE

Prior to Event	Item	During the Event
Normal.	Signal characteristics	Medium to high stress. High amplitude followed by decay. Rise is not as rapid as a rub. Seen on all rotor blades but not on vanes.
1/rev vibration on rotor blading within 3 stages of misrigged vane.	Frequency characteristics	During accel, several resonances can be seen on rotor blades. May be seen on rotors within 3 stages of misrigged vane. Blossoms at almost all per revs for one or more modes.

Onset	Operation	Escape
Improper rigging/assembly Stall damage to vane/lever(s) Fatigue failure of vane/lever		Stop test Find/fix misrigging.

Table 3. Knowledge Base Tables (Continued).

(g) ROTATING STALL

Prior to Event	Item	During the Event
Mild to heavy modulation. Low amplitude.	Signal characteristics	High amplitude. High modulation. Backward (rotor) low frequency traveling wave (.4 - .6/rev)
Several frequencies, low and higher modes. Non-integer per/rev	Frequency characteristics	Low frequency modes: 1F, 1T or 2F accompanied by .4 - .6/rev Non-periodic. Non-integer per/rev

Onset	Operation	Escape
Increasing back pressure		Decrease back pressure
Increasing speed		Reduce speed
Vane/bleed setting operation		Change vane/bleed setting
Distortion		Reduce distortion

Remarks

Rotating stall may lend to instability or surge.

(h) STALL PULSE

Prior to Event	Item	During the Event
Low to medium stress. High modulation. Modulation builds up towards stall.	Signal characteristics	Very high amplitude. Occurs very suddenly. Rapid amplitude rise and decrease. Short duration. There may be one or more pulses.
Several frequencies, mostly lower modes. Possible rotating stall. Non-integer blading frequencies. Not periodic.	Frequency characteristics	One or two modes are dominant. 1F or 1T. Short duration pulse may be repeated. Non-periodic non-integer per rev.

Onset	Operation	Escape
Rotating stall		Decrease back pressure rapidly.
Increasing back pressure		Rapid decel.
Increasing speed		
Vane/bleed setting		
Probe immersion		

Remarks

Flow reverser direction during each stall pulse from forward-to-back to back-to-forward. Very high stresses are developed. Escape must be rapid.

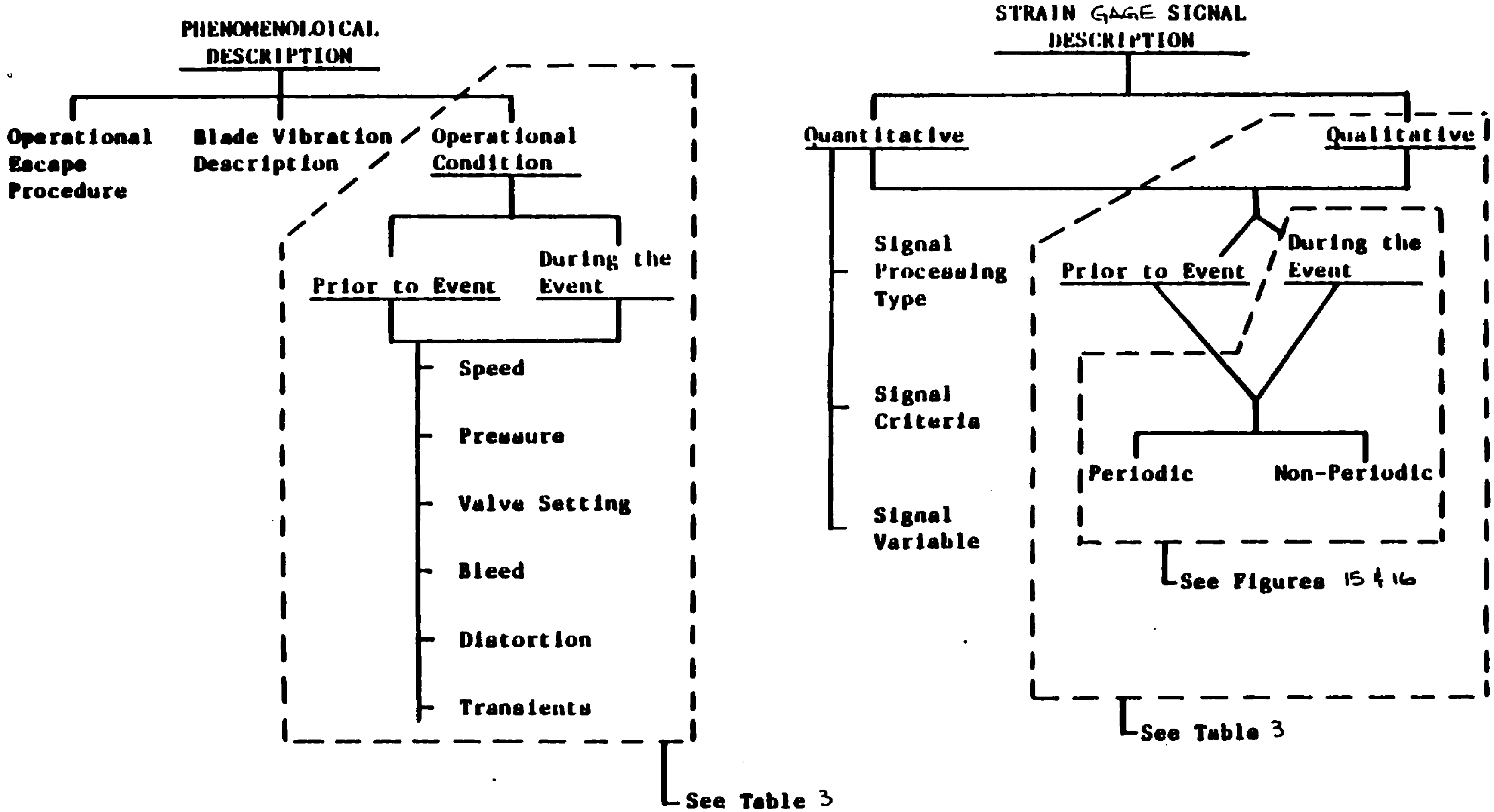


Figure 14. Taxonomic Tree for Beginning of Expert System.

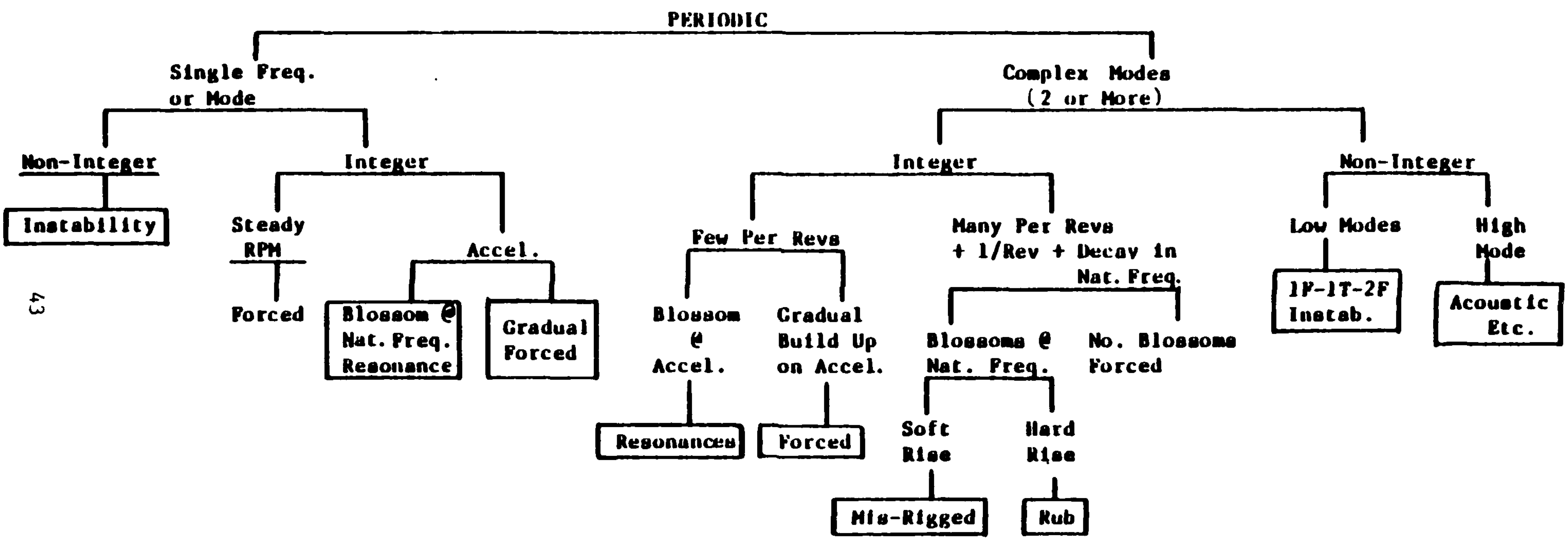


Figure 15. Taxonomic Tree for Periodic Signals.

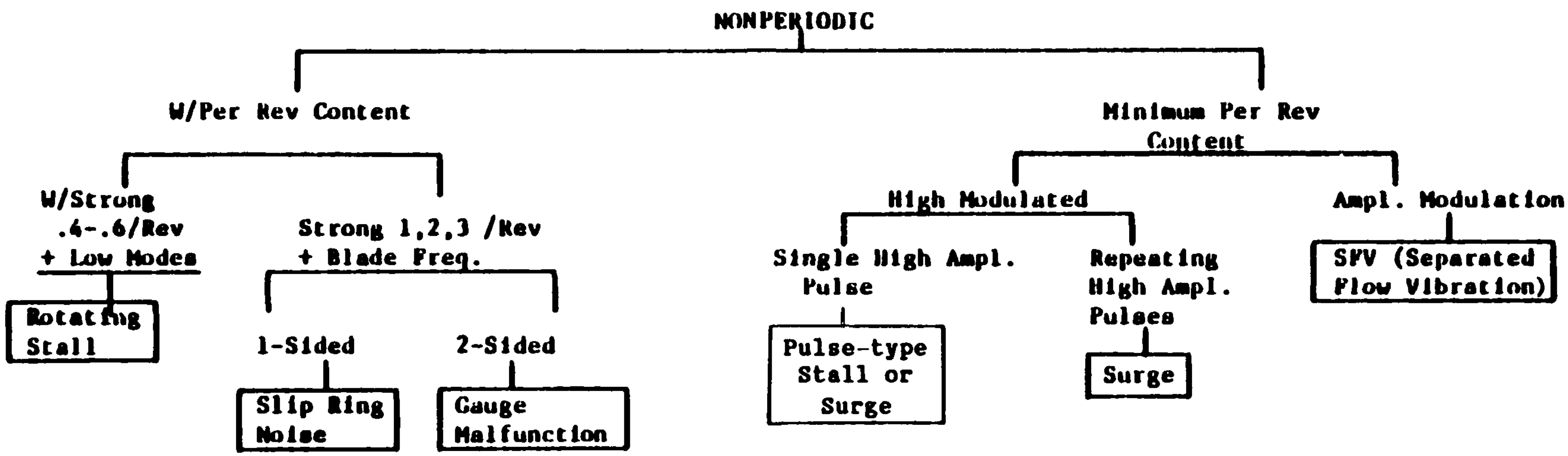


Figure 16. Taxonomic Tree for Nonperiodic Signals.

divided among the aerodynamic and thermal properties, and the vehicle mechanical operation. Thus,

<u>Air: Aerodynamic and Thermodynamic</u>

Density, temperature

Inlet pressure, pressure ratio

Weight flow, sound speed

Corrected speed

<u>Vehicle Characteristics</u>

Mechanical speed

Open/closed and location of bleed doors

Vane setting, vane schedule

Instrumentation

<u>Aeromechanical or Air and Vehicle Characteristics</u>

Bleed flow rate

Interstage match

These operating variables determine aerodynamic performance and efficiency. They also establish if the compressor is operating near stall or choke. For instance, high pressure ratio is associated with a high operating line (in a compressor pressure vs. flow curve) which is a condition at which separated flow vibration is prevalent.

Of these operational variables, the most important are the vane setting, pressure, corrected speed, density and bleed rate. The other variables may be contained implicitly in these four, such as corrected speed is an implicit function of temperature, mach number, static pressure, mechanical speed and flow rate.

3.3.2 <u>Escape Procedures</u>

Because changes to these operating conditions result directly in changes in blading vibration (amplitude and type), it follows that to avoid unsafe vibration levels, the escape procedure must consist of instructions for the magnitude and direction of changes in the operating conditions.

In Section 3.2, the knowledge base tables contain the operating conditions that lead both to the onset of the vibration types and to escape when the strain signals are unsafe. Of these variables, the compressor back pressure and rotor speed are the most obvious and quickest to change. Due to the needs of speed and safety to avoid unsafe conditions, the fewer operating variables the better. Hence, the basic operational variable for escape procedures are pressure and rotor speed. These are to avoid strain levels that could lead to imminent mechanical failure that is allowed to persist. At strain levels that are below safe limits but still considered too high for prolonged operation, the escape procedure may be more leisurely and thus can include changes in other variables. The chart in Figure 17 show the overall strain signal interpretation scheme. A closer look at the escape-action alternatives is summarized in Figure 18.

The instruction box "back-off to previous operating condition" would be used when the strain levels do not result in significant damage accumulation so that the compressor is given another chance. The "previous operating condition" are values of the pertinent operational variables in the earlier one. However, when strain amplitudes are so high that imminent damage is possible, then the "stop cock" procedure must be adopted.

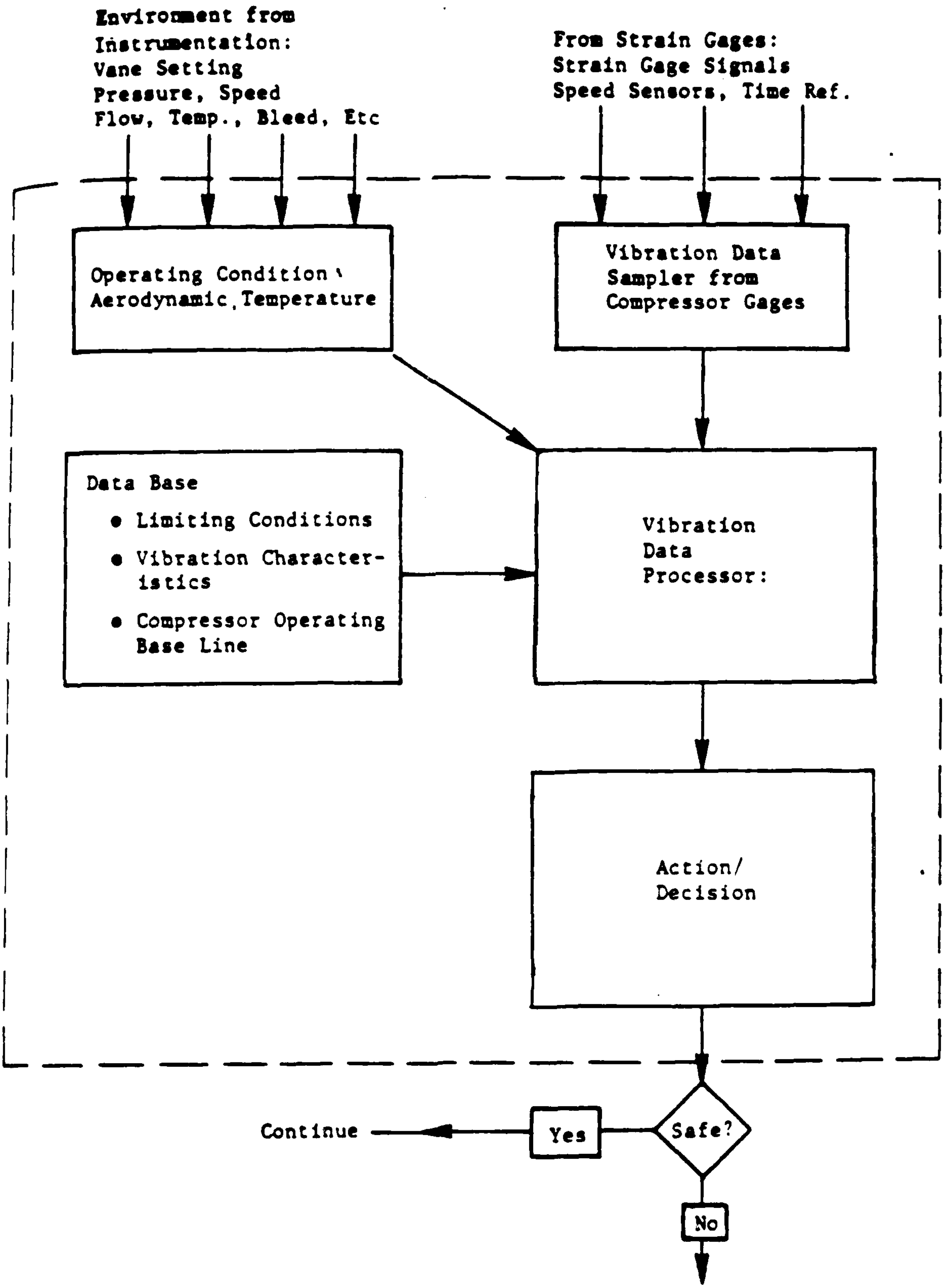


Figure 17. Flow of Information for Strain Gage Signal Interpretation and Monitoring.

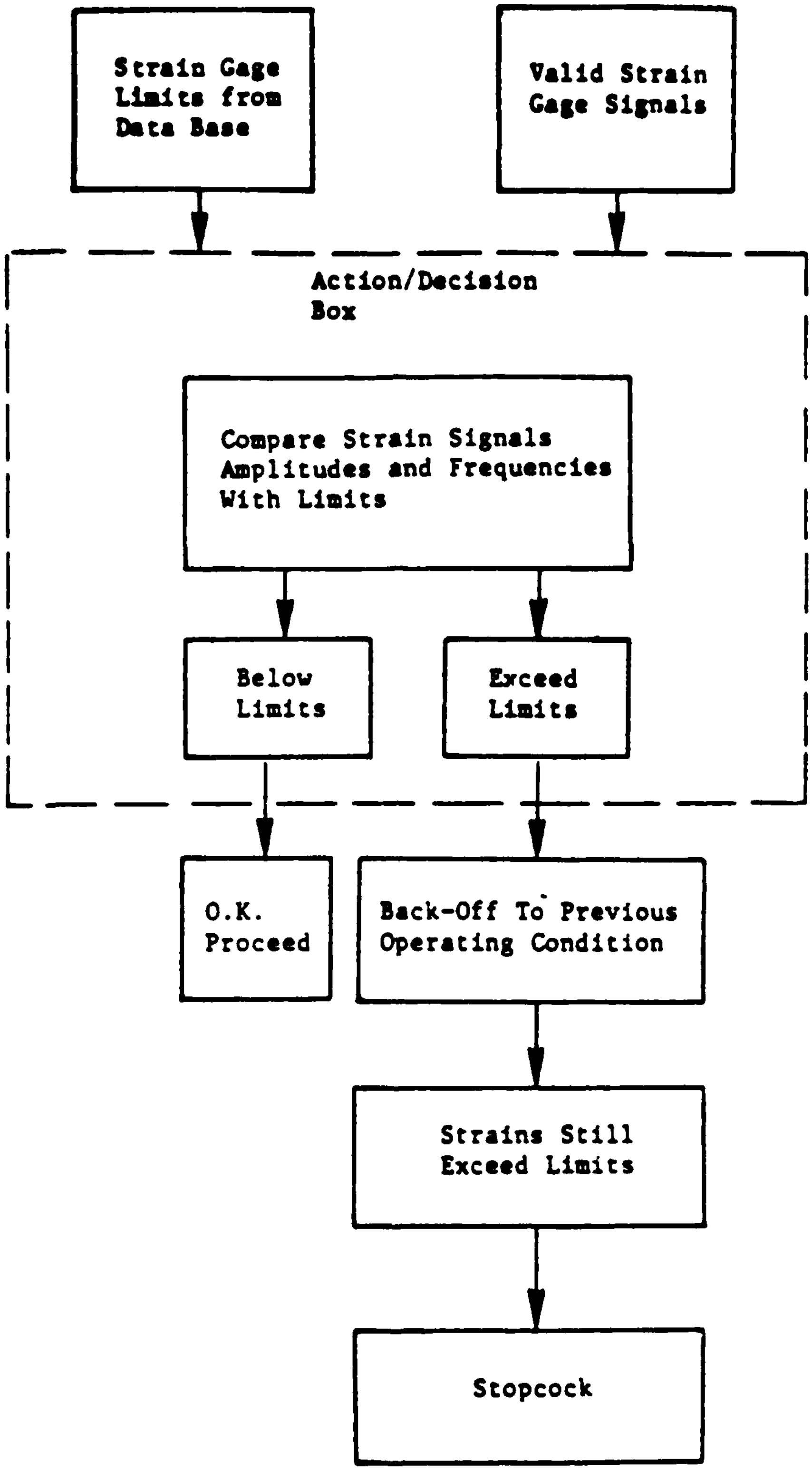


Figure 18. Action Alternatives.

4.0 HARDWARE SPECIFICATION

In the processing of dynamic strain gage information, it is necessary to utilize an expert system in order to properly identify a signal and correctly use the information during a test. An expert system, as previously noted, requires not only a data base which contains background information related to the test but it also requires real time data describing the engine conditions. These data, which are normally available to the aeromechanical engineer, include rotor speed, pressure, temperature, vane settings, fuel flow, throttling, and use of bleed air. This information is supplied in currently operational testing facilities, and by correctly interfacing the signal analysis system with the operational system, the data will be available to the expert system. The following information describes the hardware required for near real time dynamic strain gage signal interpretation.

Figure 19 depicts the signal analysis module components required to process eight channels of strain gage signals. Thirteen modules would be required to process over 100 channels of information simultaneously, as depicted in Figure 20. Each of the 13 microcomputers and the CPU would directly access the data base management system.

Specifications for the components required for each 8-channel group of inputs are as follows:

Trigger:

An analog trigger with a programmable set point will precede any digital hardware. It will be set to a threshold value by an input from the CPU (or microcomputer in its chain). Signal levels below the programmed threshold will not be allowed to pass into the system. The trigger shall have a minimum of 1 mHz frequency response for turn on time. After the trigger has been activated, the strain gage signal will pass to the processor for a minimum of one second. This time interval is the on-state time, and can be reset by any signal which exceeds the threshold setting. Signal noise will be a problem with this device and it is possible to eliminate it without reducing the capability of the signal analysis chain - but then all incoming signals would be processed.

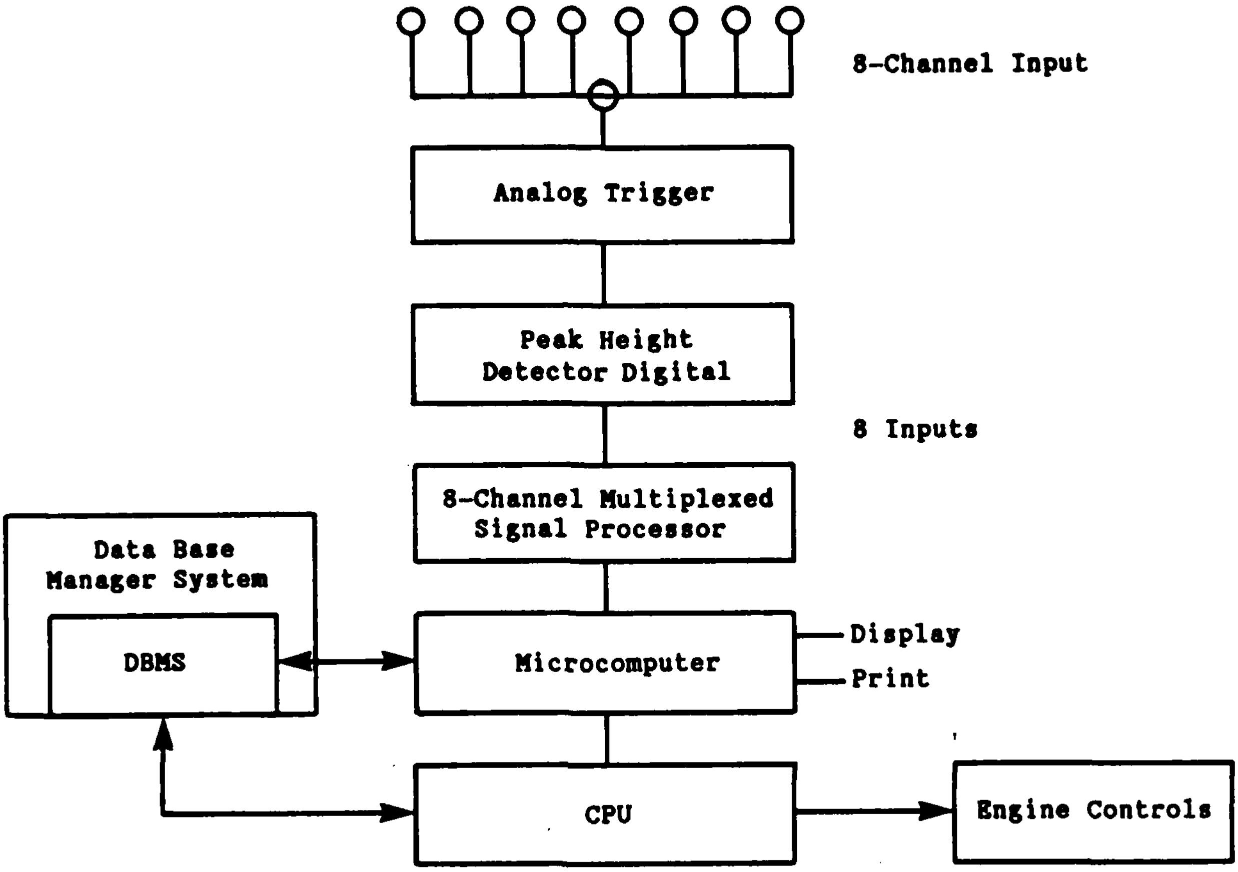


Figure 19. Signal Analysis System.

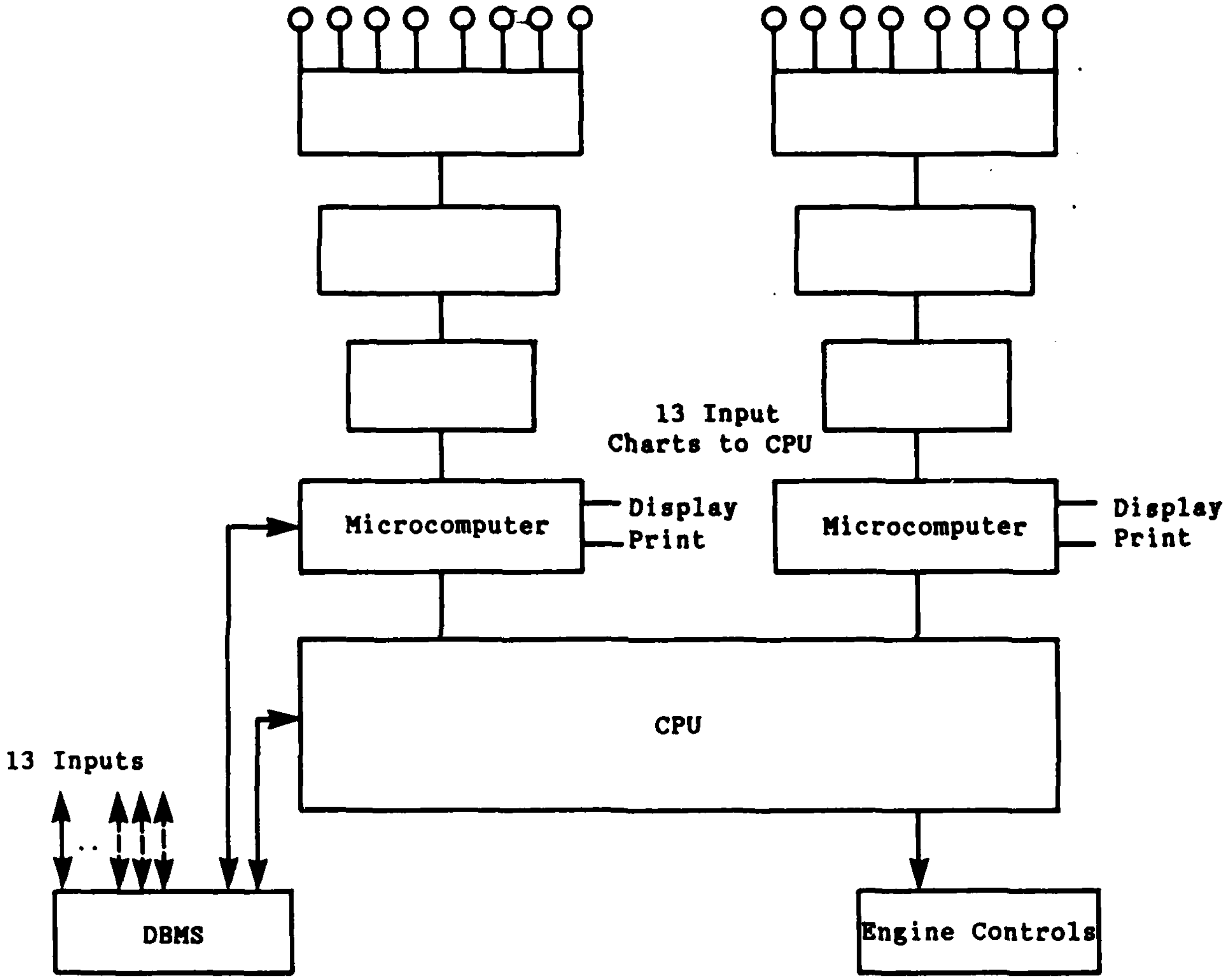


Figure 20. Signal Analysis System Configuration.

Peak Height Analyzer:

The peak height analyzer will be capable of finding the positive and negative peaks of a 50 kHz signal with an accuracy of 0.1 percent. The peak will be determined using a high speed (8 MHz) digitizer and comparator circuit. It shall have a FIFO memory with a 100k byte capacity. It will send data to the microcomputer for storage in the DBMS and for additional processing.

8-Channel Multiplexed Signal Processor:

This unit will be able to sample each of eight multiplexed signals at a rate of 150 kHz so that the multiplexing frequency must be a minimum of 1.2 MHz. These rates will provide a 50 kHz bandwidth. It will be able to perform a 1024 point FFT with both real and imaginary components in 10 milliseconds or less after digitizing the signal. In addition it can be instructed to perform a 512, 256, or 128 point transform for "quick looks" at a data stream. It will be able to perform signal averaging in the frequency domain. It will send signal analysis data to the microcomputer for storage in the DBMS and the further evaluations. An anti-aliasing filter will be incorporated in the signal analyzer to eliminate high frequency noise which might appear as data in the 50 kHz band after a Fourier transform.

Microcomputer:

This unit will be able to store two megabytes of information. It will have outputs to CRT's and the main CPU. It will be able to take data from the signal processor and from the peak height analyzer. It will run analytical routines and logic sequences. It will be able to display engineering data on CRT's and print data. It will input information to the CPU and it will interface with DBMS. It will be able to perform the analytical functions of the processor if the processor is replaced by a digitizer and antialiasing filters.

Central Processing Unit:

The central processing unit will be a large high speed computer with 20 megabytes of memory. It will be able to test for data from up to 20 input channels in under 50 microseconds. Data transfer rates of 1 megabyte/second will be possible. It will be configured to process decision matrices efficiently. For initial system development, the CPU could be an existing engine control computer system, but it would not be expected to have the capacity or speed to handle 100 strain gage signals quickly enough to provide engine control decisions in less than 250 milliseconds.

Data Base Management System (DBMS):

The proposed DBMS will follow a Relational model (see Section 5.1) and have the capability to perform parallel processing for data searches. It will limit the time required to input or output any key search to less than 5 milliseconds. The hardware for the DBMS is specified to meet system time and capacity requirements. For a single 8 channel input string, the DBMS would be a software package using the microcomputer and CPU. For multiple input strings, additional processing equipment would be necessary to meet the timing specifications of the DBMS.

The storage of data by the DBMS will require careful handling to assure that the data is useable. For example, since a 1024 point transform has 512 "bins" of real data which provides a resolution of 10 Hz for a frequency of 5120 Hz, a resolution of 10 Hz requires 0.10 second of real time sampling (the sampling window), the DBMS will need to code data from a given time frame and store the data so that it can be correlated to all the other data from the same time frame. It will also need to store data describing the "window" used to gather the data (resolution), since the resolution of the data affects the accuracy of comparisons to previously stored data.

5.0 SOFTWARE SPECIFICATION

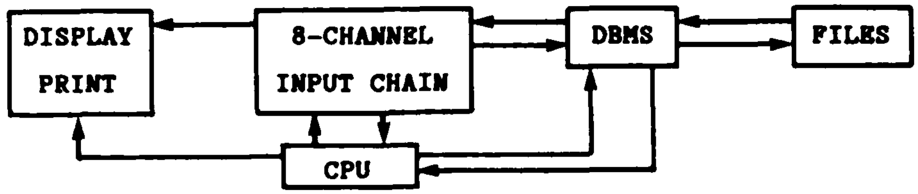
The software definition will include pretest data input requirements, on-line detail requirements, requirements for calculation and data handling, and for decision making and engine control.

To develop the software system specification, it is necessary to review the purpose of the system. The following capabilities should be available:

1. Near real time on-line processing of dynamic strain gage information during engine testing.
2. Display of significant information.
3. Initiate evasive action to prevent damage to either the test vehicle or the test facility when necessary.
4. Data storage for records.
5. Logic to enable the development of an expert system.

In terms of the required logic for the system, the highest priority requirement is to initiate evasive action to prevent damage to the test vehicle and/or the test facility during a test. This evasive action should be taken based on data from signal analyses and it must be both timely and accurate. It must be fast enough to prevent damage, but there should be sufficient flexibility to enable development vehicle operation through high stress regions to provide for complete mapping of the projected operating region.

Following in logical sequence, the next priority is to provide information to aid in analyzing the performance of the test vehicle. This requires the full interaction of the components of the system, analyzing incoming data, determining its significance, and subsequently presenting the data in a usable form. Storage of the raw data is desirable to allow off-line studies of the test, taking advantage of system post-processing capabilities. Raw analog strain gage data storage will be accomplished by continuously recording all signals on magnetic tape. Hard copy and video output display containing specific information generated from the computerized data processing will be provided. The following block diagram describes the overall functioning of the signal analysis system.



The key to the overall system capability lies with the Database Management System (DBMS) which will be discussed in the following paragraphs.

5.1 DATABASE MANAGER

The key to engineering interaction with the acquired and processed data and the related engine background information is the DBMS. This software package will control the flow of information for any data inputs or retrieval requirements initiated by any one of the microcomputers in the signal analysis string or by the engine control computer (Host). Although businesses have developed a variety of data storage and retrieval systems, it has been found that as the database becomes larger, the penalties for having a poorly designed system can become severe. Hence, the computer processing time can be greatly extended and data can be lost to the extent that an expert programmer is required to dig it out.

Therefore, several configurations have been considered for database management in a dynamic signal analysis system using dynamic Fourier taxonomy. Three primary organizational formats are used in database management systems. These are Relational, Hierarchical, and Network.

Relational formats follow set rules for a table (two-dimensional array):

1) No row can exactly duplicate any other row.
2) There must be an entry in at least one column or combination of columns that is unique for each row (the column heading is the identification key used for search operations).
3) One and only one entry is allowed in each row/column cell.
4) The rows have no specified order.

The advantages of a Relational format are:

1) Adding a new item can be thought of as adding a row and does not require squeezing data into a rigid format.
2) The table can be searched for any particular aspect of the data (column headings).

The primary disadvantage of a "Relational" database model is that a large amount of time can be consumed in searching files.

The Heirarchical model is a branched model in which each piece of information is linked to lower order attributes. It has a tree structure of one-to-many relationships as seen in Figure 21, and in the taxonomic trees of Figures 14, 15 and 16.

The Network model is a branched model in which there is many-to-many relationships between attributes as seen in Figure 22.

The major advantage of Heirarchical and Network models is that they operate rapidly. The major disadvantage of these models is that they have a rigid search format and it is difficult to collect and include information which does not follow the format.

The proposed DBMS will follow a Relational model and have the capability to perform parallel processing for data searches. This will limit the time required to input data or output any key search to less than 5 milliseconds. Based on experience gained by using the system, programs can be written to break the table into subsets for more rapid data acquisition.

In terms of system activity and productivity, the DBMS will be a major controlling factor. For a 104 signal channel input, there will be 13 of the 8 channel chains connected to the DBMS along with the system control computer. The file storage will include both volatile memory and hard disk storage.

In the overall system, each eight channel input chain has the capability to analyze signals, run decision making programs, store data and output information. The CPU has the capability to run the engine control programs,

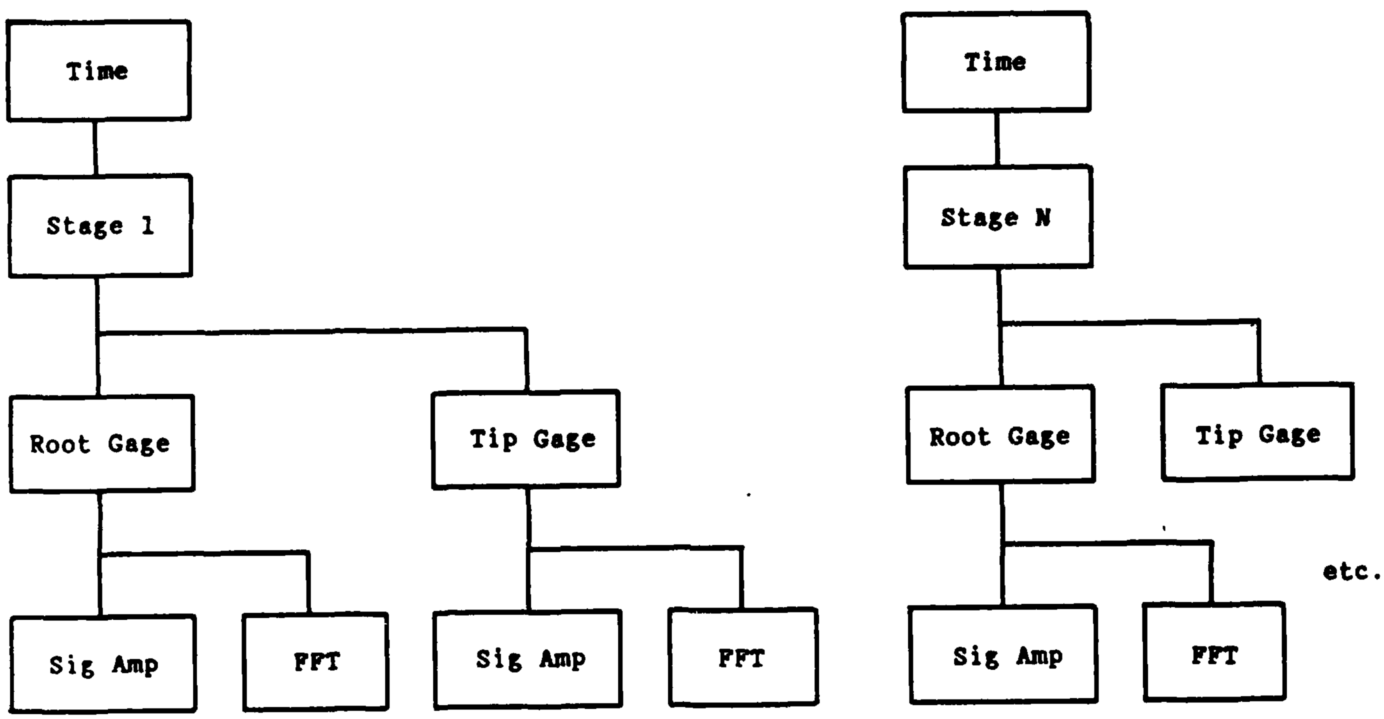


Figure 21. Heirarchical Model - Tree Structure.

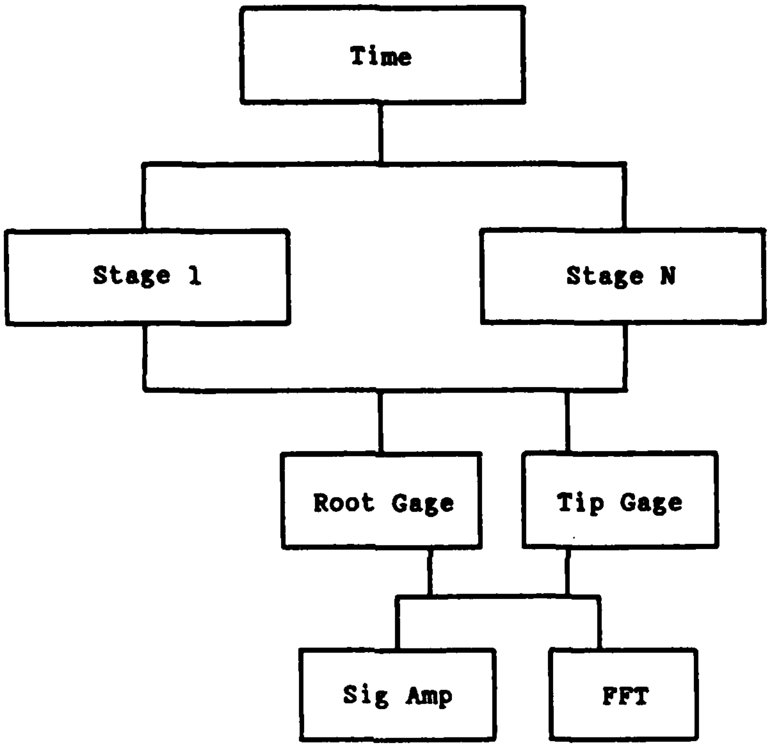


Figure 22. Network Model - Many to Many Branch Structure.

run the decision making program, store data and output information. The volatile memory of each microcomputer as specified is 2 megabytes and that of the CPU is 20 megbytes. The DBMS will work with the volatile memories in all of the input computer subsystems in parallel and will thereby have an effective 46 megabytes of volatile memory, when the system has 13 input systems. Due to the specification that data searches will be performed rapidly, in 5 milliseconds or less, and that each sub-system can access the same information, a series/parallel accessing method will be written into the DBMS to minimize the time required when two requests are made simultaneously for the same information.

The DBMS will be developed in a manner to allow expansion. For the first one or two input chains (8 channels each), a DBMS residing in the CPU would be adequate to meet system speed requirements. As the system is expanded to include the full 100 channels, the DBMS will require additional hardware to meet processing speed requirements. Fortunately, DBMS systems are commercially available which can use parallel processing and Ynet synthesizing with the proper hardware to rapidly access up to 10 billion bytes of information.

The use of a DBMS with a Relational database will make the proposed system extremely flexible. This versatile system is planned such that it will be relatively easy to implement additional software programs developed after the system is in place. In addition, using hard disc storage capabilities with the DBMS and maintaining billions of bytes of information stored over a series of engine tests, it will be possible to implement expert system program sequences so that the expert system can improve performance with experience.

As discussed in the preceding paragraphs, the DBMS is a software package which will require hard disc storage and parallel processors to function at the required speed in the full system having 13 input chains. The scope of the DBMS will be to manage all of the files which are required by the signal analysis system to function properly. Table 1 depicts the lists of data which must be available in the files for analysis by the expert system logic.

5.2 CRITERIA OF THE EXPERT SYSTEM

It is clear from Table 1 that the expert system requires a variety of data for its decision making processes. The data base contains not only tabular laboratory results from nodal analyses of blade resonances, but also engine control information from the host computer and calculated near-real time data from engine measurements. To acquire and process the engine measurements so that they can be sensibly incorporated into the data base and subsequently utilized by the expert system requires that precise definitions be applied to each measured quantity and to each processing methodology. These were described earlier in Sections 2.0 and 3.0.

One of the most challenging aspects of this work has been to translate analog descriptions of signal characteristics to the more precise and unambiguous requirements of a computer. To accomplish this, the definition of each type of vibration signal is reduced to basic measurable quantities.

Fundamental "vocabularies" have been used to construct the characteristics of the various signal types. These basic ideas are used to abstract from the real world the identifying characteristics of the signal. These signal building blocks are listed below:

- Relative Amplitude: Greater than or less than, equality
- Averaging
- Integer Versus Non-Integer
- Modulation Criterion
- Blossoming Criterion
- Valid/Invalid or Noise Criterion
- Accel/Decel Criterion
- Signal Slope: For misrigged vane versus rub

Examples of how some of these concepts break down into calculable definitions and of how they might be used in practice are given in Appendix A.

The software packages which will be written will perform functions outlined on the decision logic diagram, Figure 23. Although the functional breakdown for the hardware is outlined in Figure 24, as discussed in the

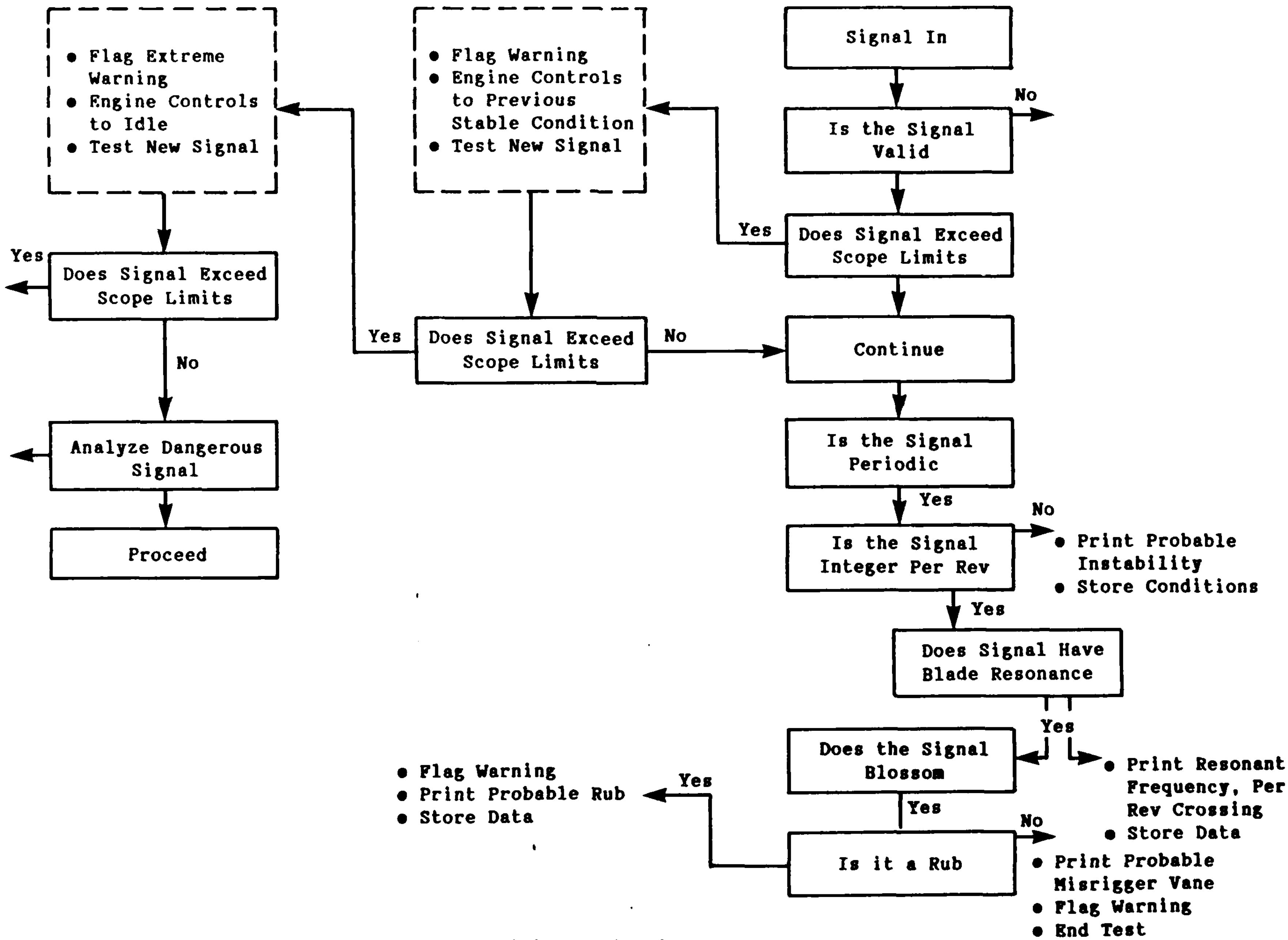


Figure 23. Decision Logic Diagram.

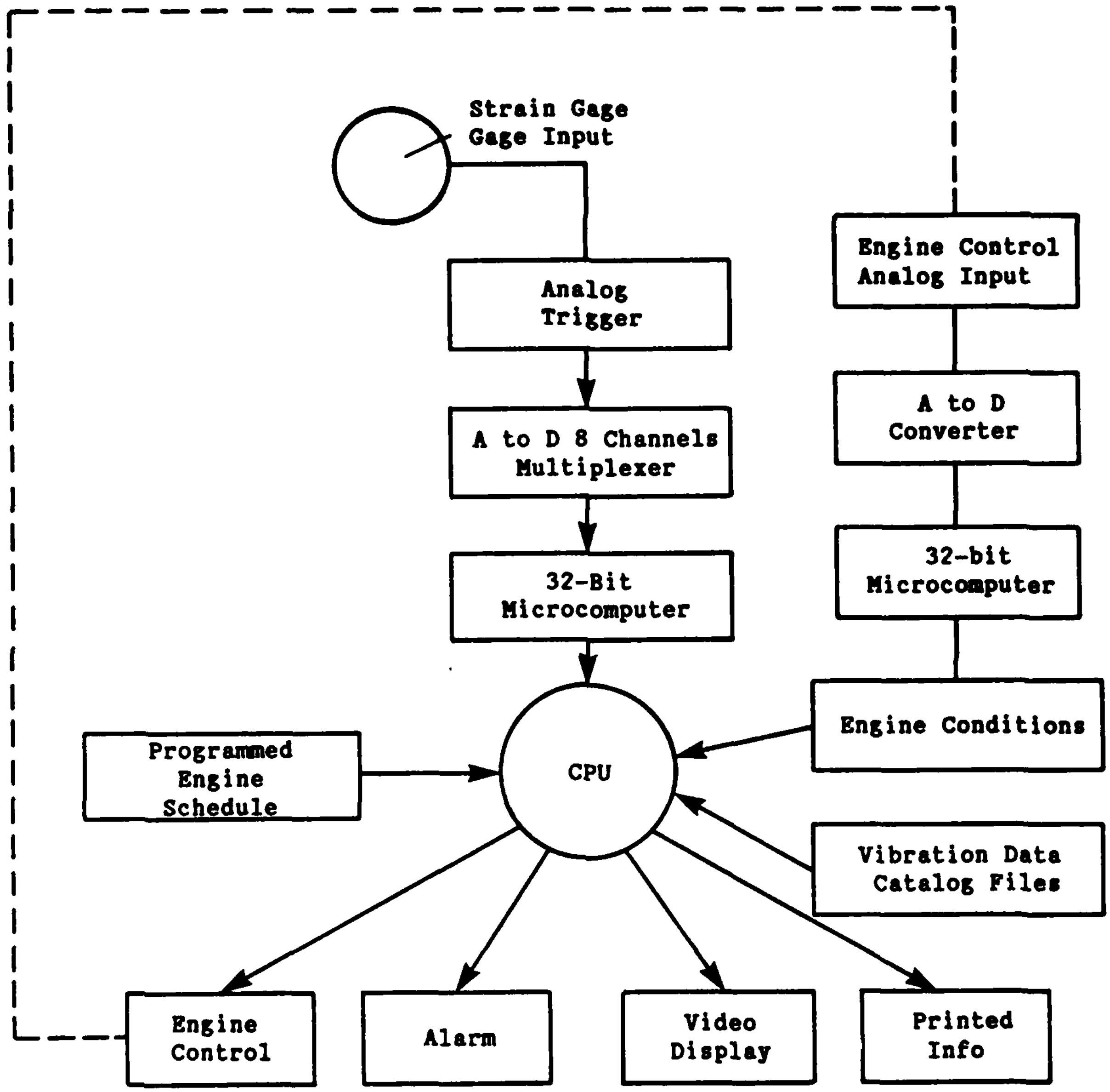


Figure 24. Hardware Information.

Section 5.1, the entire database can be accessed from any of the microcomputers. The only function which the CPU cannot share with a microcomputer is engine control.

5.3 INPUT DATA

To understand the functioning of the decision logic diagram, it is necessary to know what information is available to it. The available data is divided into three major categories with inputs as follows:

I. Historical Data from Previous Tests of Same Core Engine
   - A. Engine conditions before, during and immediately after any flagged condition.
   - B. Type of previous test, e.g. "C" cycles, TAC missions, etc.

II. Laboratory Data/Analytical Data ("updatable" with test results)
   - A. Scope limits
   - B. Test Schedule (Control Settings)
   - C. Predicted Campbell Diagram
   - D. Predicted Compressor Map

III. Test Input Data
   - A. Engine conditions
     1. Temperature
     2. Pressure
     3. Speed
   - B. Signal Data
     1. Peak height data
     2. FFT data
     3. Auto spectrum
     4. Cross spectrum
   - C. Time Markers (time of day and 1/rev)

The function of the flag warning signal is to sound a bell, turn on a light, or in some other fashion alert the test engineer and the aeromechanics engineer that a threatening condition has been reached.

5.4 SOFTWARE REQUIREMENTS

5.4.1 General

These technical requirements specify the functional capability of the individual and collective elements of the Near Real Time Signal Analysis.

All software will be written in a high level language, preferably Fortran 77. (Actually, the ideal software language would be that used in the latest expert systems - such as "LISP". However unfamiliarity with these languages, which are relatively new, precludes disucssing the requirements appropriate to them. Therefore the suggestion of Fortran 77 is based on common familiarity.) Said software is to be as user friendly as possible while retaining its ability to operate in real time.

5.4.2 Software Configuration

The software will consist of the following modules:

- Executive/Driver module
- Acquisition module
- DBM module
- Processing module
- Graphics module
- Utilities module
- Operator Interface module

5.4.3 System Requirements

The Near Real Time Signal Analysis System is a data acquisition and processing system. It will provide an interactive tool for both post-test data and on-line data analysis in a real-time environment. The following processes will be performed concurrently in most instances.

- Data acquisition
- Fast Fourier Transforms
- Engineering units conversions

- Data archiving
- Interactive graphical display of data
- Software development utilities

The processes are to be handled by the software described below. To support this work with operating system software, diagnostic software and application program developed software is provided (the host). As a minimum, the operating system will be:

- A priority driven real-time system
- Simultaneous multi-processing system
- Multi-tasking
- Multi-user for program development
- Dynamic allocation of system resources
- Supports Fortran 77
- Supports Quick Return I/O.

Compatibility of all element of the system must be assured. Maximum consideration will be given to reliability and maintain- ability of all software.

5.5 MODULE SPECIFICATION

Key requirements of each of the system components are listed below.

5.5.1 Executive/Driver Module

The Executive/Driver module will perform the following functions:

- Schedule jobs via the microprocessor operating system
- Delete jobs via the operating system
- Hold jobs via the operating system
- Resume jobs via the operating system
- Process Intertask Control Blocks (ICB)

5.5.2 Acquisition Module

The acquisition software will acquire data from three different pieces of hardware. They are the signal analyzer, microprocessor, and host computer.

The Acquisition Module will consist of the following sub-modules:

- Download Front-end Setup Parameters (PSETUP)
- Data Acquisition from Digital Inputs (RTPACQ)
- Configuration Interpreter (CONFIG)
- Auto Calibration Processor (ACAL)
- Driver/Root (DRVROT)

5.5.3 Download Front-End Setup Parameters (PSETUP)

The PSETUP sub-module software will allow the user to specify the following parameters.

- Sample rate (including external source)
- Number of channels to be sampled
- Number of data samples in each data window
- Internal/external start trigger or source
- Pre and post delay of data window after trigger
- Order in which channels are to be sampled
- Cutoff frequency of the programmable filters
- Gains
- Selectable number of FFT output lines
- Selectable data store time

5.5.4 Data Acquisition from Digital Inputs (RTPACQ)

5.5.4.1 Inputs

104 Digital Inputs (DI's) - The DI's will consist of 4 groups of 32 bits for each of 13 channels.

5.5.4.2 Scan Rates

The DI's will be scanned at rates specified in the configuration. This rate will be used by RTPACQ sub-module to tell it how often to sample the DI's.

5.5.4.3 Averaging and Data Labeling

The speed data is acquired over the same time period in the data sample. The speed data will be averaged to generate one speed value. This speed value will be time labeled along with the data sample and stored on disk.

5.5.5 Auto Calibration Processor (ACAL)

Functions: to request RTPACQ to read the calibration data and perform a channel level check and a channel skew check before constructing the calibration tables.

5.5.6 Driver/Root (DRVROT)

Function: to control the execution of the sub-modules in the Acquisition Module.

5.6 DATA BASE MANAGER (DBM)

The DBM will interact with the host and input strings to effectively perform the following functions:

- Retrieve data from the data base
- Store data in the data base
- Perform any necessary housekeeping within the data base
  a. To delete files
  b. To add files
  c. To update files
  d. To update directories
  e. To compress the data base
- Build, update, and release Module File Active Tables

The DBM is the only interface into the data base for all modules described in this specification.

5.7 PROCESSING MODULE

The Processing Module will consist of a set of application programs used to process raw acquired data. Initially the Processing Module will consist of the following sub-modules but will be able to grow as more types of processing are defined. This module will not be necessary if a signal analyzer is used in place of a digitizer and antialiasing filters. (The prime consideration being hardware cost.)

- Fast Fourier Transform (FFT)
  - a Forward
  - b. Inverse
  - c. Variable point 128, 256, 512, 1024, 2048
- Low Pass Digital Filtering (LPDFIL)
- Full Scale Data Reduction (FSDR)
- Engineering Units Conversion and Calibration (EUCC)

5.8 GRAPHICS MODULE

Will be able to present dynamic strain gage data in the following ways:

- Campbell Diagrams
- Spectrum Plots (amplitude vs. frequency)
- Phase Plots
- Correlation Plots
- Wave Forms
- Overall Levels
- Modal Analysis
- Tracking Frequency
- Spectrograph (frequency/amplitude vs. time)
- X/Y Plots

5.9 UTILITIES MODULE

Initial functions of this module will be:

- To generate tabulated output listings of data in the data base
- To create, edit and delete input files (configs)
- Transfer data over the Synchronous Data Link to the DMS

5.10 OPERATOR INTERFACE MODULE

This module will present a user-friendly menu driven operator interface into the Dynamic Data Reduction System Software package.

5.10.1 Logic Module

The logic module shall call for data from the DBMS as required to follow the sequence outlined in the logic diagram.

6.0 CONCLUDING REMARKS

6.1 SUMMARY OF RESULTS AND CONCLUSIONS

The principal results may be stated simply that the strain gage signals from aeromechanical vibrations of rotor blades and vanes have been collected, examined, classified and generalized in a taxonomic sense. A unified and rational system has been developed for the interpretation of strain gage signals in terms of certain characteristics amenable to computer programming. Included are specifications for both hardware and software.

In the process of this work, variables most suited for classification, called taxonomic variables, are found. These are obtained by an FFT processing of the digitized strain gage time-series data. It is for this reason that the methodology is identified as Dynamic Fourier Taxonomy.

The results are summarized in greater detail in the following sections according to each of the four specific tasks:

Task I - Collection and Classification of Strain Gage Signals
Task II - Generalization and Taxonony of Strain Gage Signals
Task III - Hardware Specification
Task IV - Software Specification for Signal Interpretation

6.2 TASK I - COLLECTION AND CLASSIFICATION OF STRAIN SIGNALS

A large number of magnetic tapes from instrumented blades and vanes in many engines have been collected, played back and examined. The engine types encompass GE's stable of turbine engines from the small turboprops, to turbojets and to the large high bypass turbofan engines. Test conditions include all the phases that are investigated during engine development including stall investigations, performance, inlet distortion, bodie bursts, steady state, transients, variable vane optimization and many others. The blading types are almost as numerous: cantilevered, fixed-root and part span shrouded, tip shrouded, variable and fixed vanes and pin roots.

From this task, several obvious things are apparent, and these are that strain signals are not distinguishable by types of engine, blading fixity (shrouded, fixed-fixed, etc.) or by whether they are rotor blades (rotating) or vanes (static). This is a great simplification in the effort of generalization of strain gage signals.

The vibration strain gage signal patterns given as a history of amplitudes vs. time acquire their characteristic shapes by natural frequencies of the blading and aerodynamic environment.

Finally, the various representations of the strain gage signals were obtained by FFT processing. These indicated that certain strain gage signal properties are the most straight-forward and simplest variables to classify and generalize the strain gage signal types. These properties of the signal are derived from the raw time series data by the fast Fourier transform techniques. These properties or taxonomic variables are mainly peak amplitude history, frequency spectrum with relative amplitude and Campbell diagram.

Though other variables can be obtained, such as power spectrum, spectral densities and others, those chosen here are the simplest and most readily understood. Also one must keep in mind that the prinicpal objective of a computer operated system is to assure the compressor's mechanical survival, so time is of the essence. The fewer the variables, the less time it would take a computer to evaluate and interpret strain signals.

6.3 TASK II - GENERALIZATION AND TAXONOMY OF STRAIN SIGNALS

The taxonomic variables and strain gage samples determined in Task I were used to obtain the abstractions of the essential characteristics of the various vibration strain signal. These were generalized so that the vibration types can be discriminated from one another.

A system of dynamic Fourier taxonomy was developed which discriminates the various strain gage signals according to a hierarchic model involving both the taxonomic variables (spectra, peak amplitude history, etc.) and aerodynamic operating conditions as well as the state of the signals and operating conditions just prior to - and at - the time or event of interest.

Consequently, these are given both as tables of vibration diagnostics and a taxonomic tree. Since the method of classification is a system, a glossary of terms and rules are provided. Included are necessary background knowledge and limiting conditions and rules for using them. Using the language of expert systems, these comprise the knowledge base which is summarized graphically in Figure 1.

The most important characteristics of the various vibration strain gage signals can be best described by the following:

(1) Uniformity or non-uniformity of the peak amplitude and/or its rate of increase. This includes the phenomena of amplitude modulation, the blossoming at resonances or instability and the peak/cycle slopes important for on-line identification of rubs and misrigged vanes.

(2) Frequency spectrum and the relative contributions of natural modes to the total response. The ratio of frequency-to-rotor speed is a requirement that helps distinguish forced response from instability and separated flow vibrations.

(3) The aerodynamic environment is a pre-condition of each vibration type. Certain vibrations such as rotating stall, surge, and stall instability, are most likely to occur at high operating lines or back pressure.

Included in Task II are the necessary pre-test data such as strain gage safety limits, blading natural frequencies, and escape procedures. This pre-test information must be determined (outside this contract) to provide the means to evaluate the severity of test strain gage signals, identify the modes of vibration, and direct an escape procedure when the stress level is unsafe. The initial escape procedure is the "back-off" or return to the previous safe operating condition. In cases where strain levels still remain prohibitively high, the alternative is the "stop cock" or rapid deceleration to idle speed conditions.

6.4 TASK III AND TASK IV: SPECIFICATIONS FOR HARDWARE AND SOFTWARE

The desired characteristics of the aerodynamic data base and strain gage signal processing, handling and management equipment have been developed. These have been translated into specifications of the requisite hardware. These specifications are dictated by the highest and lowest (stationary) frequencies of the dynamic data, and the logic for evaluating and identifying them over a relatively short time interval. Included are equipment for data storage and output display.

Similarly, specifications for software have been developed. The Fortran 77 language has been suggested. The logic of the signal interpretation proposed here follows the principles of expert systems so that the software must have the capacity to handle data and logic for raw time-series data, obtain the taxonomic variables and utilize them in the rules and heuristics of strain gage signal interpretation. In addition, the software is required to be able to "trace back" to the set of logic and information with which it's conclusions are reached. This allows a check of the computer by an aeromechanics expert, and is especially valuable in the development of the computer guided monitoring system.

6.5 RECOMMENDATIONS

This effort may be one of the first to design an automatic computer diagnostic system for dynamic and high frequency phenomenon. Though similar expert systems have been developed in other fields such as medicine, structures and pattern recognition, these do not have the stringent constraint of time. Because dynamic strain gage signals from compressor blading are at high frequencies, the time it takes for fatigue failure to occur is very brief, sometimes only seconds. So there is a severe requirement in time and speed to identify the problem if it exists, and to change the compressor operating condition to a safer one quickly and decisively.

Being at an embryonic stage, the presently developed dynamic Fourier taxonomy of strain gage signal and its attendant data base may be overly optimistic in its immediate goals. This work was accomplished in less than two years on dynamic phenomena, whereas expert systems such a "Mycin", "Caduceus", "Sacon" and others have taken as long as 10 years or more. In these allied fields, it had taken a concentrated and protracted cooperation of the experts and the knowledge engineers, who have had many years of experience with this branch of artificial intelligence and its more natural computer software language.

It is therefore recommended that implementation of results of the present work employ a cooperative effort of aeromechanical experts and those familiar with knowledge engineering or expert systems. One must realize that this is a relatively new field and though much can be learned from the allied fields of pattern recognition, diagnostics and others, it may also have something to contribute as well.

7.0 REFERENCES

1. Parker, D., Berg, D.F. and Gallardo, V.C., "Optimization of Vane and Bleed Settings," AFWAL-TR-2028, April 1980 (ADB052663).

2. "A Proposal for Strain Gage Signal Interpretation," Volume 1, submitted in response to RFP F33615-82-R-2263, USAF ASD WPAB, P82-131, Sept. 27, 1982.

3. Cardinale, V.M., Bankhead, H.R., and McKay, R.A., "Experimental Verification of Turboblading Aeromechanics," Presented at 56th Symposium of AGARD Propulsion and Energetics Panel, Turin, Italy, October 1980. Published in AGARD-CP-293, January 1981.

4. Baker, J.E., "Insights to Practical Applied Aeromechanics," General Electric T.M. No. 78-501, September 1978.

5. Bendat, J.S. and Piersol, A.G., "Measurement and Analysis of Random Data," John Wiley and Sons, Inc., N.Y. 1966.

6. Danforth, C.E., "Designing to Avoid Fatigue in Long Life Engine," paper presented at the National Aeronautic Meeting New York, N.Y., April 25-28, 1966, sponsored by the Society of Automotive Engineers (SAE)

7. Danforth, C.E., paper presented at a meeting of the AIAA, 1966.

8. Sources on Artificial Intelligence and Expert Systems

   a. A college text on Botany or Comparative Anatomy.

   b. Shortliffe, E.H., Fagan, L.M., "Expert Systems Research: Modeling the Medical Decision Making Process," paper presented at the Workshop on Integrated Approach to Patient Monitoring at University of Florida at Gainesville, 5-6 March, 1982.

   c. Minsky, M., "Why People Think Computers Can't," Technology Review Magazine, Nov./Dec. 1983, pp. 65-81.

   d. Alexander, T., "Why Computers Can't Out-Think the Experts," Fortune Magazine, Aug. 20, 1984, pp. 105-118.

   e. Shurkin, J.N., "Expert Systems: The Practical Face of Artificial Intelligence," Technology Review Magazine, Nov./Dec. 1983, pp. 72-78.

   f. Taylor, J.H., Frederick, D.K., "Expert Systems Concepts for Computer Aided Engineering," G.E. CR/DC Rept. No. 84CRD127, Class 1, Schenectady, N.Y., May 1984.

APPENDIX A - TAXONOMIC GLOSSARY

From the block diagrams, it is clear that the expert system requires a variety of data for its decision making processes. The data base contains not only tabular laboratory results from nodal analyses of blade resonances, but also engine control information from the host computer and calculated near-real time data from engine measurements.

To acquire and process the engine measurements so that they can be sensibly incorporated into the data base and subsequently utilized by the expert system requires that precise definitions be applied to each measured quantity and to each processing methodology. To accomplish this, the definition of each type of vibration signal is reduced to basic measurable quantities. Some of the questions requiring software definition are:

(1) Relative Magnitudes: "Larger Than", "Smaller Than", is 2.05 larger than 1.95 or are they equal by definition?

(2) Equality: What criterion is used to conclude two values are equal, e.g., is 2.115 = 2.16?

(3) Integer: What criterion is used to define an integer. For example: 2.05 can be considered as the integer 2; similarly, 2.98 can be considered as the integer 3.

(4) Modulation Criterion: This defines the measure and the degree of amplitude modulation. How is a random change in signal amplitude or an irregular change in signal amplitude distinguished from a modulated signal?

(5) Averaging: The basic non-uniformity of signal amplitudes requires a means of averaging them prior to comparison with established limits

or with amplitudes before or after an event. Amplitudes must be averaged over defined sampling lengths for a uniform reduction in noise levels measured.

(6) The Analysis Threshold Check: This is a number which is set for a given scope calibration. It is set so that it will trip if any signal input is more than some predetermined percentage of a critical amplitude.

(7) Validity Test (Noise Criterion): How does the computer differentiate between faulty strain gages, slipring or telemetry noise and large amplitude stress signals?

Examples of how some of these concepts break down into calculable definitions and how they might be used in practice are presented hereinafter.

A.1 Acceleration

A steady state operating condition will be defined to be whenever there is no more than 0.2% speed variation or fluctuation. Say an engine is operating at 12,000 rpm (200 Hz), this criteria permits no more than $\pm$24 rpm ($\pm$0.4 Hz) speed fluctuation for a steady state definition. Speed will be calculated from a 1/rev signal and a fixed frequency pulse counter. A counter frequency of 1 MHz would give 5000 pulses between each 1/rev signal for a 200 Hz egine speed, and the $\pm$0.4 Hz deviation would be $\pm$10 pulses. To determine acceleration or deceleration, an average pulse count will be taken for three successive sets of ten revolutions and the pulse count difference will be compared between each set. If there is a trend, e.g., set 1 set 2 set 3, and there is more than 0.2% change, then the engine is accelerating. If there is less than 0.2% change in speed, regardless of the trend, the engine will beconsidered at a steady state point.

This method of determining acceleration can be implemented as a parallel computational effort that can be accessed by the CPU for decision making input.

A.1 Amplitude & Modulation

The amplitude of a strain gage signal is the peak height of the signal at the time of interest. This is the measure of the current stress level and is usually expressed in ksi-da, where da means double amplitude or peak-to-peak value. For a strain gage signal whose peak height data has been recorded over some time interval, the amplitude modulation will be defined by:

$$AM = (H_{max} - H_{min})/H_{max}$$

where

AM = Amplitude modulation index

H_{max} = Maximum stress over the interval

H_{min} = Minimum stress over the interval

and

0	AM	0.10	denotes nearly constant amplitude
0.10	AM	0.35	denotes slight modulation
0.35	AM	0.65	denotes moderate modulation
0.65	AM	0.80	denotes heavy modulation
0.80	AM	1.00	denotes severe modulation

A.3 Analysis Threshold Check

Since the strain gage analog signals will be continuously recorded on magnetic tape, it is not necessary to computer process all strain gage data - only that at a level high enough to be of interest. An analog trigger with aprogrammable threshold is provided for each strain gage signal. The threshold level for each strain gage is dependent upon that particular strain gage safety limit. The threshold will have been determined from bench test data and engineering analysis for each gage.

A.4 Campbell Diagram

A Campbell diagram, constructed for a particular rotor, is a plot of blade frequency versus rotor speed showing curves of natural frequencies of various vibratory modes of the blades, with pertinent integral-order lines (or per rev's) superposed. When the blade modes are from analysis, each being represented by a single curve, this is called an analytical Campbell diagram, see Figure A1.

FFT processing of the strain gage data adds the additional dimension of stress amplitude, and it is sometimes called a test Campbell diagram, see Figure 1. Here an almost vertical line is plotted, at incremental rpm's throughout the speed range, the center of which is at the response frequency and the length representing the double amplitude stress level.

A.5 Integer

Once the frequency spectrum of a strain gage signal is obtained, the computer then must determine which of the FFT calculated frquencies correspond to integral multiples of rotor speed. Hence it is necessary to define "integer" so the computer, after dividing each frequency by the rotor speed, can make this assessment. Although this definition seems trivial, it is highly unlikely that an exact integral order would ever by calculated.

Then, for a calculated value X, if I(X) is the standard integer value of X, an integral order is defined by:

Case I: $X-I(X) \quad 0.05$

Case II: $X-I(X-1) \quad 0.05$

For Case I, the value of the integer is I(X). For Case II, the value of the integer is I(X)+1. These two equations will distinguish the two possible conclusions, e.g., 2.02 would be the integer 2 and 2.98 would be the integer 3.

A.6 Peak Height

The peak height time series is constructed by recording the successive positive and negative peak amplitudes of the time varying analog strain gage signal. The peak height analyzer is capable of finding the peaks of a 50 kHz signal with an accuracy of 0.1 percent. This data is used to determine the validity ot a signal and to trigger alarm/escape procedures when unsafe stress conditions have been encountered. This time series is fundamental for interpreting signals with unique shapes and for determining the degree of signal modulation.

A.7 Signal Averaging

Averaging a number of signal segments is a signal enhancement technique used to improve the signal-t noise ratio by lowering the noise content of the signal. The start of each signal segment is initiated by a reference signal, usually the 1/rev signal. Averaging can be accomplished in either the time or the frequency domain. Time domain averaging does not preserve nonsynchronous frequency components of the signal as does frequency averaging. Hence, if synchronous signal components (e.g., from resonance) are of interest, time averaging may be used; if nonsynchronous signals (e.g., from flutter) are of interest, frequency averaging may be used.

A.8 Validity Test (Noise Criterion)'

Two types of noise occur frequently during engine testing; noise due to faulty gage and slip ring noise. Slip ring noise is identified by being one-sided in the same domain. The computer needs to check the signal amplitude for consistently negative or positive values. This is easily done by testing signal amplitudes. The signal will be defined as one-sided if no more than 10% of the maximum signal amplitude is found below (or above) the zero setting.

Noise due to a faulty gage can be identified by comparing the signal to signals from similar gages on the same stage and by performing an average. If the signal in question is more than 20% greater in magnitude (at a peak value) than similar gages on the same stage and its average approaches zero when averated in per rev sets, it is from a malfunctioning gage and the gage will be disconnected.

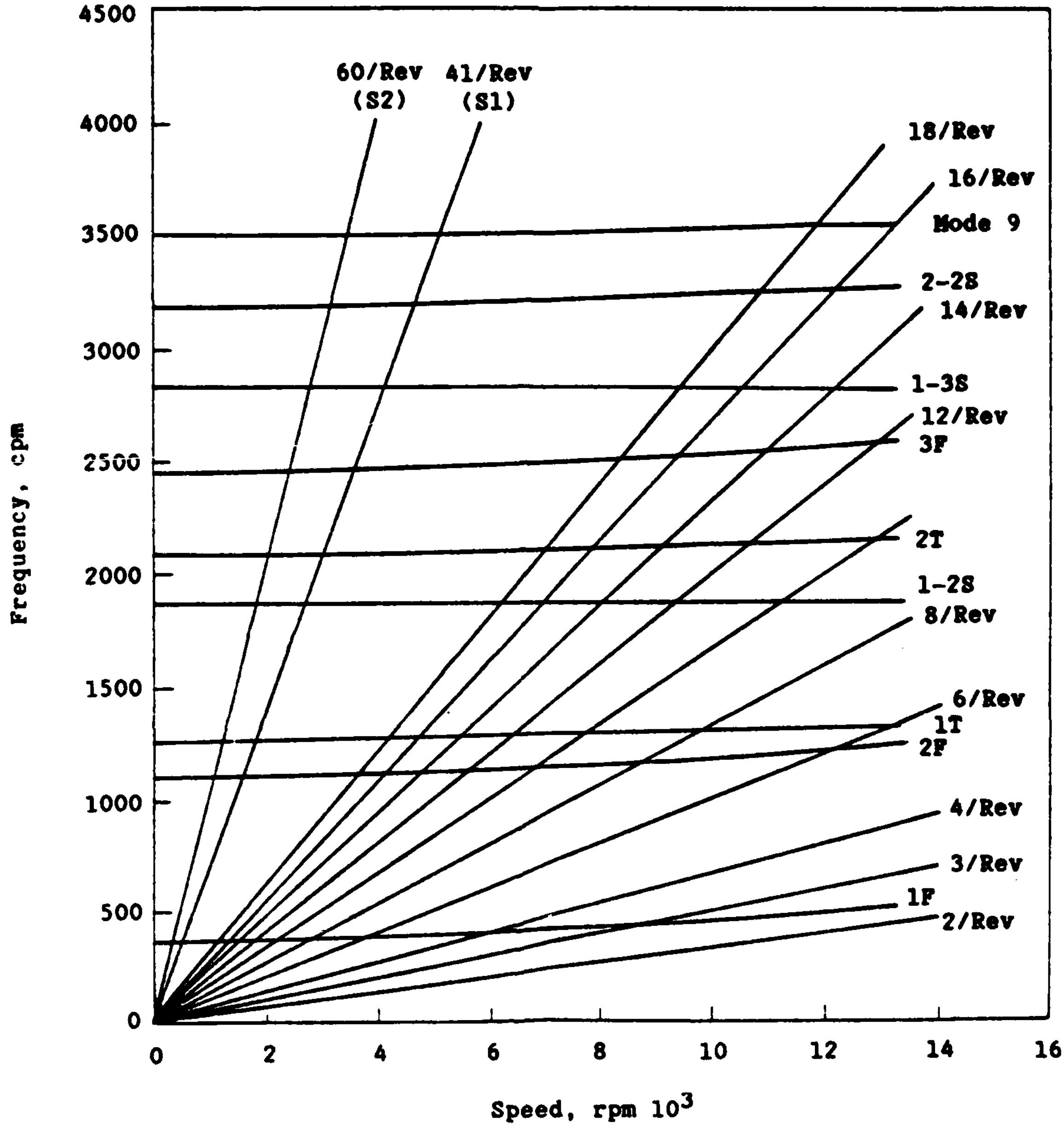


Figure A1. Analytical Campbell Diagram.

U.S.Government Printing Office: 1986 — 748-061/60538

END

1-87

DTIC